US Army Corps
of Engineers
Construction Engineering
Research Laboratory

AD-A240 003

USACERL Interim Report P-91/43
July 1991

A Prototype Construction Duration Estimating System (CODES) for Mid-Rise Building Construction

by
Ruofei Sun
Guruprasad N. Rao
Diego Echeverry
Simon Kim

This interim report describes the concepts that support the development of the prototype Construction Duration Estimating System (CODES) for mid-rise building construction. The prototype system: (1) breaks down the construction process into major activities, (2) sequences activities logically, and (3) estimates approximate activity durations of major construction activities. While the CODES prototype is limited to office and residential construction projects, through an enhancement of the user interface, project-specific features can be input to the prototype to modify its produced schedules. CODES is presently in its validation and testing phase.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1991	Interim

4. TITLE AND SUBTITLE
A Prototype Construction Duration Estimating System (CODES) for Mid-Rise Building Construction

5. FUNDING NUMBERS
PE 62734
PR AT41
TA SA
WU AF0

6. AUTHOR(S)
Ruofei Sun, Guruprasad N. Rao, Diego Echeverry, and Simon Kim

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Construction Engineering Research Laboratory (USACERL)
PO Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER
IR P-91/43

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
HQUSACE
ATTN: CEMP-CP
20 Massachusetts Avenue, NW.
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This interim report describes the concepts that support the development of the prototype Construction Duration Estimating System (CODES) for mid-rise building construction. The prototype system: (1) breaks down the construction process into major activities, (2) sequences activities logically, and (3) estimates approximate activity durations of major construction activities. While the CODES prototype is limited to office and residential construction projects, through an enhancement of the user interface, project-specific features can be input to the prototype to modify its produced schedules. CODES is presently in its validation and testing phase.

14. SUBJECT TERMS
Construction Duration Estimating System (CODES)
knowledge based systems
construction scheduling

15. NUMBER OF PAGES
56

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

FOREWORD

This study was conducted for the Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Project 4A162734AT41, "Military Facilities Engineering Technology"; Work Unit SA, Task AF0, "Construction Control Knowledge Schedule." The HQUSACE technical monitor was Mr. James Jones, CEMP-CP.

This research was performed by the Facility Systems Division (FS) of the U.S. Army Construction Engineering Research Laboratory (USACERL). The principal investigator was Dr. Diego Echeverry. Dr. Michael J. O'Connor is Chief, USACERL-FS. The USACERL technical editor was Mr. William J. Wolfe, Information Management Office

COL Everett R. Thomas is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

CONTENTS

		Page
	SF 298	1
	FOREWORD	2
	LIST OF FIGURES AND TABLES	4
1	INTRODUCTION	5
	Background	
	Objectives	
	Scope	
	Mode of Technology Transfer	
2	PROCEDURE	7
	Overview	
	Knowledge Acquisition	
	Activity Definition	
	Activity Logic	
	Activity Durations	
	Weather and Procurement Constraints	
3	PROTOTYPE IMPLEMENTATION	15
	Overview	
	Example Run	
	Summary of Workshop To Review the CODES Prototype	
4	SUMMARY	26
	REFERENCES	26
	APPENDIX A: Enclosure Implementation	28
	APPENDIX B: Comprehensive Code Listing	31
	DISTRIBUTION	

FIGURES

Number		Page
1	Activity Breakdown (Steel Frame Alternative)	9
2	Flow Chart of CODES Operation	16
3	Activity Topics and Attributes	17
4	Building Type Prompt	19
5	Construction Start Date Prompt	19
6	Prompt for Determination of User Control of System Values	20
7	Prompt for Determination of Weather Considerations	20
8	Weather Conflict Warning	21
9	Parameter Selection for Value Change	21
10	New Value for Selected Parameter	22
11	Bar Chart	23
12	Text File	24
A1	Flow Chart of Enclosure	29

TABLES

1	Major Activities of Mid-Rise Building Construction	10
2	Major Activities and Logic Relationship of Steel-Framed Mid-Rise Building Construction	11
3	Example Run Input and Output	18

A PROTOTYPE CONSTRUCTION DURATION ESTIMATING SYSTEM (CODES) FOR MID-RISE BUILDING CONSTRUCTION

1 INTRODUCTION

Background

The actual duration of both military and civil works construction projects is often substantially different from the estimates or schedules made prior to initiation of construction. In fiscal year (FY) 1988, actual duration of military construction projects took an average of 17 percent longer than estimated. Similarly, actual duration of civil construction projects averaged 19 percent longer than estimated.

More accurate estimates will require: (1) improved duration estimation and project schedule generation prior to construction start, (2) enhanced schedule control during construction, and (3) a more structured process of synthesizing the lessons learned in current or concluded projects, to benefit the planning and control of future projects. This research focuses on the first of these actions, the development of enhanced computer tools to support the construction duration estimation and project schedule generation tasks.

Commercially available computer software provides some limited support to produce project schedules; however, the actual schedule generation process is done manually. This manual process includes: (1) activity identification, (2) activity logic determination, and (3) duration estimation. Automated tools are needed to support these tasks.

Objectives

The objective of this phase of work was to develop a project-scheduling, knowledge-based prototype system to estimate construction duration, specifically, to support activity identification and sequencing, and activity duration estimation. The objectives of the concluding phase of this study will be to verify and enhance the current working prototype, by: (1) conducting a hands-on review by engineering and construction district personnel to obtain direct feedback from potential users, (2) incorporating the recommendations made from that review and from the workshop conducted as a part of this study, and (3) testing the prototype by applying the program to schedule records from selected building projects performed in the past by Corps of Engineer districts.

Approach

The overall approach was to apply a Knowledge-Based Systems (KBS) technique that addresses the generation of construction schedules. The work is to be accomplished in four phases—two described in this interim report, and two to be the subject of a future report:

1. A literature survey was done, and skilled construction schedulers were interviewed to determine how to: (a) break down a construction project into major activities, (b) estimate durations for those major activities, and (c) establish a logical sequence to execute these major activities.

2. This acquired scheduling knowledge was represented in a prototype KBS, the Construction Duration Estimating System (CODES). An expert system developing tool called KnowledgePro[1] was used to implement the system.

3. Contact will be made with potential CODES users. If feedback is received from them early during the tool development phase, the resulting product will be altered to better address their needs. A workshop was held with participants from different Corps of Engineers district offices to obtain their feedback.

4. Finally, field testing and validation is necessary to refine the tool to directly address user needs.

Scope

CODES focuses on the scheduling of mid-rise buildings of a residential/office nature. It is able to schedule projects with up to two underground floors, and assumes basic site work and very simple excavation. CODES's analysis is valid for typical floor sizes from 5000 to 20,000 sq ft* per typical floor, and schedules only major activities.

The present report describes the concepts involved in the development of an initial working prototype of CODES. It does not describe a final product. A final product will be developed after the field testing and validation phases are concluded.

Mode of Technology Transfer

It is anticipated that CODES may become material for Huntsville division courses. Further technology transfer issues will be addressed during field testing in coordination with test sites.

---

[1]KnowledgePro ™, IBM-PC version by Beverly and William Thompson (Knowledge Garden, Inc., Nassua, NY, 12123, 1988).
*1 sq ft = 0.093 m^3

2 PROCEDURE

Overview

CODES uses a KBS technique to develop enhanced computerized support for estimating construction duration (further sources for information on KBSs are listed in the "References" section at the end of this report). The application of a KBS technique incorporates the following steps: (1) survey of experienced construction schedulers to acquire knowledge of scheduling practices; (2) formalization and representation of the acquired knowledge in the selected software platform; and (3) validation and testing of the resulting prototype system. This report discusses the concepts supporting the development of the initial CODES prototype. Validation and field testing are in progress.

Knowledge Acquisition

Two main sources of expertise were addressed: publications and construction industry skilled schedulers. The interaction with industry schedulers was given priority. Construction schedulers from several construction firms were interviewed:

1. J.S. Abercici Construction Company Inc., St. Louis, MO
2. Duke Construction Company, Indianapolis, IN
3. Korte Construction Company, St. Louis, MO
4. W.E. O'Neil Construction Company, Inc., St. Louis, MO
5. Turner Construction Company, Chicago, IL.

At the time of the interviews, all interviewed schedulers had at least 10 years' scheduling experience, mainly in building construction. This phase of the work was performed under a different work unit, and was reported separately.[2]

To accommodate their tight schedules, construction schedulers were interviewed in two ways. Some discussions were based on schedules that the schedulers had produced in the past. The alternative approach was to select a mid-rise building (a 10-story residential building), for which complete design information was available, and to request the scheduler to guide the interviewer through the production of a schedule for the construction of this facility.

The goal of the knowledge acquisition effort was to develop a representation of the information obtained using the selected KBS platform that was suitable for translation into computer logic. This was accomplished by: (1) transforming an amorphous body of knowledge into a set of concepts, rules, and facts expressed in English language (Formalized Knowledge), and (2) representing a subset of this Formalized Knowledge in a syntax understandable by the KBS platform (KnowledgePro). The main concepts formalized and represented here are discussed in the sections below.

Activity Definition

Construction of today's complex buildings includes a large number of activities or tasks. Schedule

---

[2] Diego Echeverry, *Factors for Generating Initial Construction Schedules*, Draft Technical Manuscript (TM) (U.S. Army Construction Engineering Research Laboratory [USACERL], July 1991).

approach is known as hierarchical planning. A major premise of this work, confirmed through the knowledge acquisition process is that, at the level of major activities, one can produce a reasonable duration estimate.

Focusing on major activities alone provides an overall project construction perspective (Figure 1). These major activities are collections of more detailed activities. Table 1 lists the abbreviated names used in CODES for these major activities.

Activity Logic

Essential to construction planning is the sequencing of activities to deliver the constructed facility. Activity sequencing logic in part depends on the way building components are physically related to each other. Activity sequencing also responds to other factors, like interaction among crews and equipment during construction time. For instance, one crew or type of equipment may damage the work performed by other crews. To prevent such damage, the operation of potentially damaging work is scheduled before the installation of more fragile work. For this reason, first floor finishes are performed last.

Table 2 shows the logic relations of the major activities considered here, specifies preceding activities, and also indicates the type of precedence relationship, which is either: (1) a start-to-start relationship (SS), or (2) a finish-to-start relationship (FS). A lag (time between activities) is associated with each precedence relationship, representing the time delay, in weeks, of each activity. For instance, the activity "Site&Foundation" is preceded by the activity "Mobilization" with a finish-to-start relationship and a lag of zero weeks. The prototype uses specific activity sequences, based on typical construction practice:

1. Site and foundation work is preceded by mobilization. (Contractor mobilization to the site is a prerequisite to start construction. The first construction activity is normally to prepare the site and then to proceed with foundation work.)

2. Frame erection is preceded by foundation work. (The frame is supported by the foundation.)

3. Roof frame erection is preceded by structural frame erection. (The roof frame is supported by the structural frame.)

4. Concrete deck placement is preceded by structural frame erection. (If the frame alternative is a steel frame, it is assumed that each floor slab consists of a composite metal-concrete deck. The placement of the different floor concrete decks follows the frame erection three floors behind. This responds to the fact that the metal floor decks support their corresponding concrete decks, and that enough distance should be present between the concrete floor casting and the structural frame erection.)

5. Fireproofing of the structural frame is preceded by concrete deck placing. (If the frame alternative is a steel frame, typical construction practice involves its fireproofing with a sprayed compound. Because the crew that performs the spraying requires a firm working surface, the fireproofing of a floor is normally preceded by the placing of the floor's concrete deck. One floor is kept between these two operations as a buffer to avoid the cracking of the sprayed compound under the metal deck, from the loads imposed by the casting of the next floor's concrete deck.)

6. Roofing is preceded by the roof frame erection. (The roof is supported by the roof frame.)

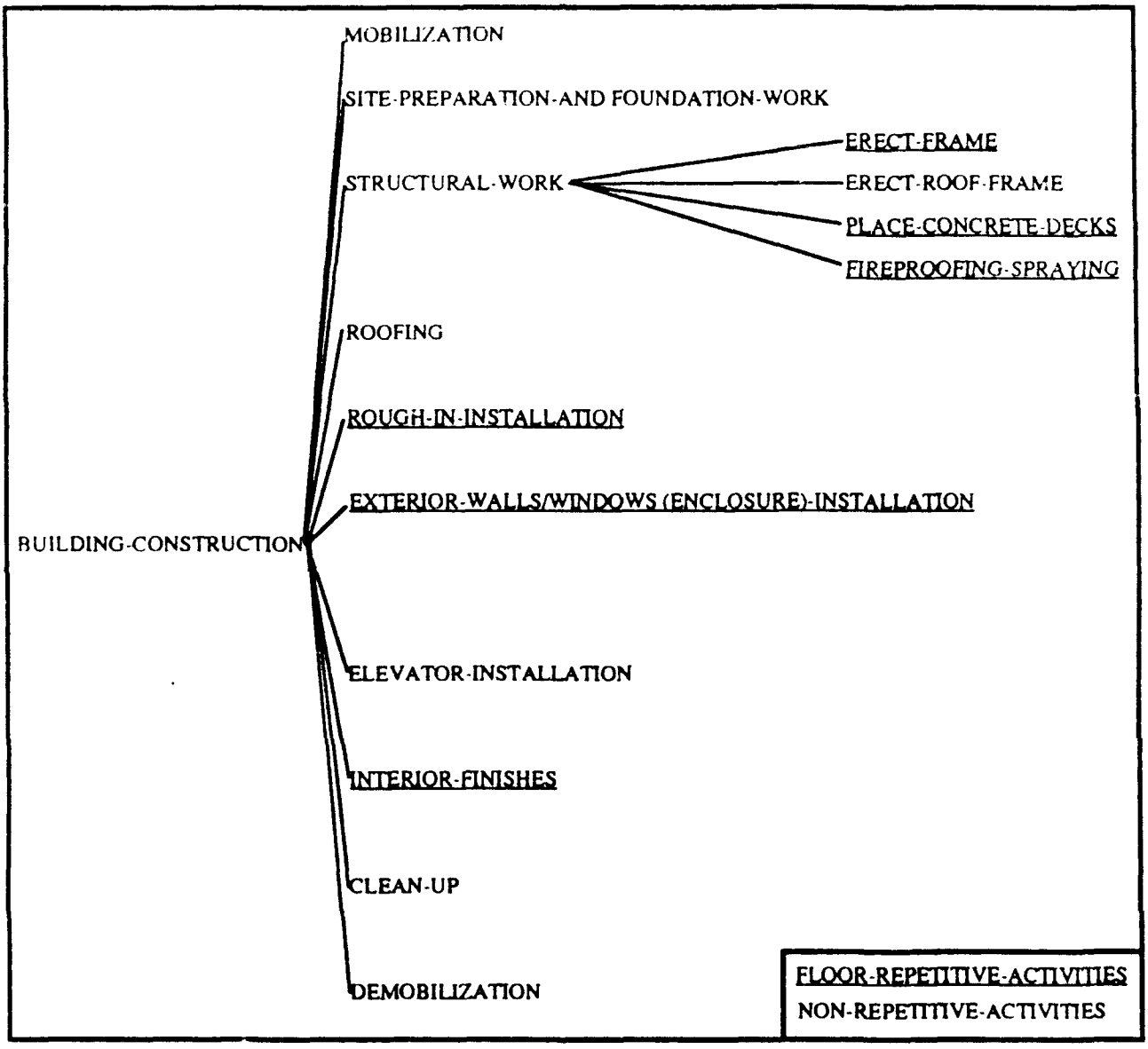

Figure 1. Activity Breakdown (Steel Frame Alternative).

Table 1

Major Activities of Mid-Rise Building Construction

Activity (Full Name)	Activity (Prototype Abbreviation)*
Mobilization	Mobilization
Clean site and construct foundation	Site&Foundation
Erect frame	Erect_frame
Erect roof frame	Erect_roofframe
Place concrete decks	Place_concr_deck
Fireproofing	Fireproofing
Roofing	Roofing
Install elevator	Instal_elevator
Rough in	Rough_in
Enclosure (exterior walls and windows)	Wall_enclosure
Interior finish basement 2nd floor	Int_finish_fl_b2
Interior finish basement 1st floor	Int_finish_fl_b1
Interior finish 2nd floor	Int_finish_fl_2
Interior finish 3rd floor	Int_finish_fl_3
Interior finish 1st floor	Int_finish_fl_1
Clean up	Clean_up
Demobilization	Demobilization

*The activity name is abbreviated in order to accommodate the system output of bar chart along with labels in one screen width.

Table 2

Major Activities and Logic Relationship of Steel-Framed Mid-Rise Building Construction

Activity	Preceded by	Type	Lag*	Duration
Mobilization				2
Site&Foundation	Mobilization	FS	0	4 - 10
Erect_frame	Site&Foundation	FS	0	Pace1 × No. of Flr**
Erect_roofframe	Erect_frame	FS	0	1
Place_conrc_deck	Erect_frame	SS	Pace1 × 3	Pace1 × No. of Flr
Fireproofing	Place_concr_deck	SS	Pace1 × 2	Pace1 × No. of Flr
Roofing	Erect_roofframe	FS	0	2
Instal_elevator	Roofing	FS	0	>= 12
Rough_in	Fireproofing	SS	Pace1 × 2	Pace1 × No. of Flr
Wall_enclosure	Fireproofing	SS	Pace1 × 2	Pace2 × No. Flr Above***
Int_finish_fl_b2	Wall_enclosure	SS	Pace2 × 2	5 - 8
	Roofing	FS	0	
Int_finish_fl_b1	Int_finish_fl_b2	SS	Pace2 × 1	5 - 8
Int_finish_fl_2	Int_finish_fl_b1	SS	Pace2 × 1	5 - 8
Int_finish_fl_3	Int_finish_fl_2	SS	Pace2 × 1	5 - 8
Int_finish_fl_1	Int_finish_fl_n	SS	Pace2 × 1	9
Clean_up	Int_finish_fl_1	FS	0	5
Demobilization	Clean_up	FS	0	2

* Units of Lag and Duration are weeks.

** Pace1 is the duration per floor of Erecting Frame.

*** Pace2 is the duration per floor of Wall_enclosure construction, which must be equal to or greater that Pace1.

7. Elevator installation is preceded by roofing. (The installation of the elevator equipment requires the weather protection of an impervious roof.)

8. Rough-in work is preceded by fireproofing. (If the frame alternative is a steel frame, the rough-in work typically follows the fireproofing operation. Because the fireproofing is performed by spraying a compound that affects other crews, a one-floor buffer is kept between these activities.)

9. Rough-in work is preceded by frame erection. For the steel frame case, rough-in work is preceded by the application of fireproofing. In the cast-in place concrete frame case, rough-in work is directly preceded by the frame erection activity. In both cases rough-in work is also performed concurrently with framing activities (embedded conduit pipes, slab sleeves, etc.) and therefore normally it is not relevant for total duration calculation.

10. Wall enclosure is preceded by fireproofing. (If the frame alternative is a steel frame, the wall enclosure typically follows the fireproofing operation. Since the fireproofing compound affects other crews, a one-floor buffer is kept between these activities.)

11. Wall enclosure is preceded by frame erection. For the steel frame case, wall enclosure is preceded by the application of fireproofing. In the cast-in place concrete frame case, wall enclosure is directly preceded by the frame erection activity.

12. Interior finishes are preceded by wall enclosure work and roofing. (The interior finishes require a weather-protected environment provided by the exterior walls and the roof.)

13. The interior finishes are performed by a number of crews that successively progress through each floor. Typically, these crews include plumbing, electrical, heating, ventilation, and air-conditioning (HVAC), wall finishes, floor surfacing, ceiling, and door/window/glazing crews. As a consequence, there is an overlap in the execution of interior finishes for the different floors. This is represented here by having floor finishes in floor "i" precede floor finishes in floor "i+1," with a start-to-start relationship and a lag equal to the progression of the exterior walls installation. The reason for this lag is that the interior finishes need the weather protection offered by the wall enclosure.

14. First floor finishes are performed last in the interior finishes sequence. This is because the crews operating in the building typically enter and exit through the first floor, and could damage finishes already in place.

15. Final clean-up follows the completion of interior finishes.

Activity Durations

For preliminary scheduling, experienced schedulers establish approximate activity durations based on general building size and on past experience. The intention here was to acquire the rules of thumb used to establish approximate durations. The determination of optimal activity durations, performed through resource allocation and leveling, is beyond the scope of this work.

Rules of thumb were acquired to determine default durations for the different activities considered. While these default durations may vary for specific projects, they do provide a base for a reasonable duration estimate. Moreover, CODES provides the user with the capability to override its default values. CODES assumes the following activity durations:

1. Mobilization: A default duration of 2 weeks is defined for this activity.

2. Site Preparation and Foundation Work: For this activity, three possible cases are considered:

a. For buildings with no basement, the default duration is 4 weeks.
b. For buildings with one basement, the default duration is 6 weeks.
c. For buildings with two basements, the default duration is 10 weeks.

These durations assume close-to-ideal circumstances (good soil, no dewatering required, no underpinning, etc.).

3. Frame Erection: The duration of this activity depends on the number of floors in the building. For the ranges of floor area (5000 to 20,000 sq ft of typical floor area) addressed here, the default duration is calculated on the basis of a frame erection pace of one floor per week. In the case of a steel frame, the concrete deck installation activity follows three floors behind, at the same pace. Fireproofing follows the concrete deck placing, two floors behind, also with the same pace.

4. Rough-in Work: The rough-in follows the frame erection pace. The default duration is set as the number of floors times the frame erection pace.

5. Roof Installation: A default duration of 2 weeks is used for this activity.

6. Elevator Installation: If an elevator is required, its default duration is computed as the maximum of: (1) 12 weeks, or (2) the time interval in weeks between roofing completion and first floor completion.

7. Wall Enclosure: The exterior walls and windows installation duration is also related to the number of floors. The default duration is calculated on the basis of a progression pace of 2 weeks per floor.

8. Interior Finishes: The interior finishes activity is broken into interior finishes for each floor. The first floor normally takes longer to be finished, because the work required for the lobby is labor intensive. The default duration for the first floor finishing is 9 weeks. The default durations for finishing the other floors are related to the degree of interior partitioning. If the floors are highly partitioned (as in residential construction), the default duration for their interior finishes is set to 8 weeks per floor. For moderately partitioned floors, the default duration is 5 weeks per floor.

9. Final Clean-up: A default duration of 5 weeks is given to this activity for final clean-up and punch list procedures.

10. Demobilization: This activity has a default duration of 2 weeks.

Weather and Procurement Constraints

It is possible to perform any type of work in almost any weather if enough protection and resources are available. However, it is expensive and time demanding to install temporary weather protection for unprotected weather-sensitive activities. Experienced schedulers consider the constraints of expected weather conditions.

The weather considerations observed from the interviewed schedulers are restricted to the Midwest region, the location of most of the scheduling cases analyzed. However, regardless of geographical location, a construction schedule must be checked against local expected weather conditions and appropriate schedule adjustments should be made. Schedulers usually consider the following weather guidelines.

1. Site Preparation and Foundation work should not begin before early Spring (approximately mid-March). This prevents: (1) the difficulty of performing earthwork operations in frozen ground, and (2) potential problems of performing concreting operations (foundations) in cold weather.[3]

2. Building enclosure (roof, skin) should be complete by late Fall (approximately the end of November) if interior finishing is scheduled during winter time. This allows the progress of interior finishes into an enclosed environment. Heating is then facilitated and moisture protection enhanced.

3. Concrete casting, spraying of fireproofing, and masonry work should not proceed during cold weather. These activities involve materials that require temperatures well above freezing to set and cure adequately.

Procurement time is the time associated with fabrication and delivery of items to be installed during construction. No matter how carefully and precisely construction operations are planned, substantial delays can be expected if there is insufficient or inaccurate consideration of procurement constraints. Nontypical items are especially critical from a procurement perspective. Items like structural steel, elevators, glazed curtain walls, etc. require careful procurement planning.

[3] *ACI Manual of Concrete Practice, Part 2: Construction Practices and Inspection; Pavements*, ACI88 (American Concrete Institute, Detroit, Michigan, 1988).

3 PROTOTYPE IMPLEMENTATION

Overview

As mentioned earlier, the platform used is KnowledgePro, an expert system tool written in Turbo Pascal. KnowledgePro runs on IBM PC/XT, AT, or compatible computers with a minimum of 640K random access memory (RAM) and a hard disk. KnowledgePro has a backward-chaining inference engine and other KBS basic features.

The objective of the prototype development phase was to produce a tool able to estimate project construction duration, based on a representation of the activity definition, sequencing, and duration estimation issues described above. CODES is the initial working prototype of this tool. Additional development, validation, and field testing of CODES are still required.

Figure 2 shows the overall system operation. A typical CODES session starts with a welcome window and system description. After the initialization of some global variables, the user is asked to provide the necessary information related to the particular project being scheduled. The main system objective is to set up a list of all the major activities and the related values (Figure 3) and to output it to the screen and to text files.

The attributes of each activity are determined with rules and critical path method (CPM) calculations. Main activity attributes are: activity duration, precedence relationships, lags associated to precedence relationships, and start and finish times. The attributes determining rules are summarized in the LAG and DURATION columns of Table 2, and in Figure 3.

All major activities (like Mobilization, Rough in, Roofing, etc.) are considered as frames (or topics) and the logical relationships between them are described by attributes and their values. The attributes can be activity, predecessor, relation, lag, duration, early start time, and early finish time. The rules are expressed in an "IF--THEN--ELSE" form and are used to determine activity duration and predecessors.

Appendix A provides a detailed explanation of how major activity information is incorporated in the prototype. This is done by showing how enclosure is implemented. Appendix B provides a comprehensive program source code listing.

Example Run

The input to the system is menu-driven. Table 3 lists example run input and output for a six-story office building with a floor area of 15,000 sq ft. The building has one basement, a steel frame, and a masonry and windows enclosure. Some corresponding screen displays are shown in Figures 4 through 10.

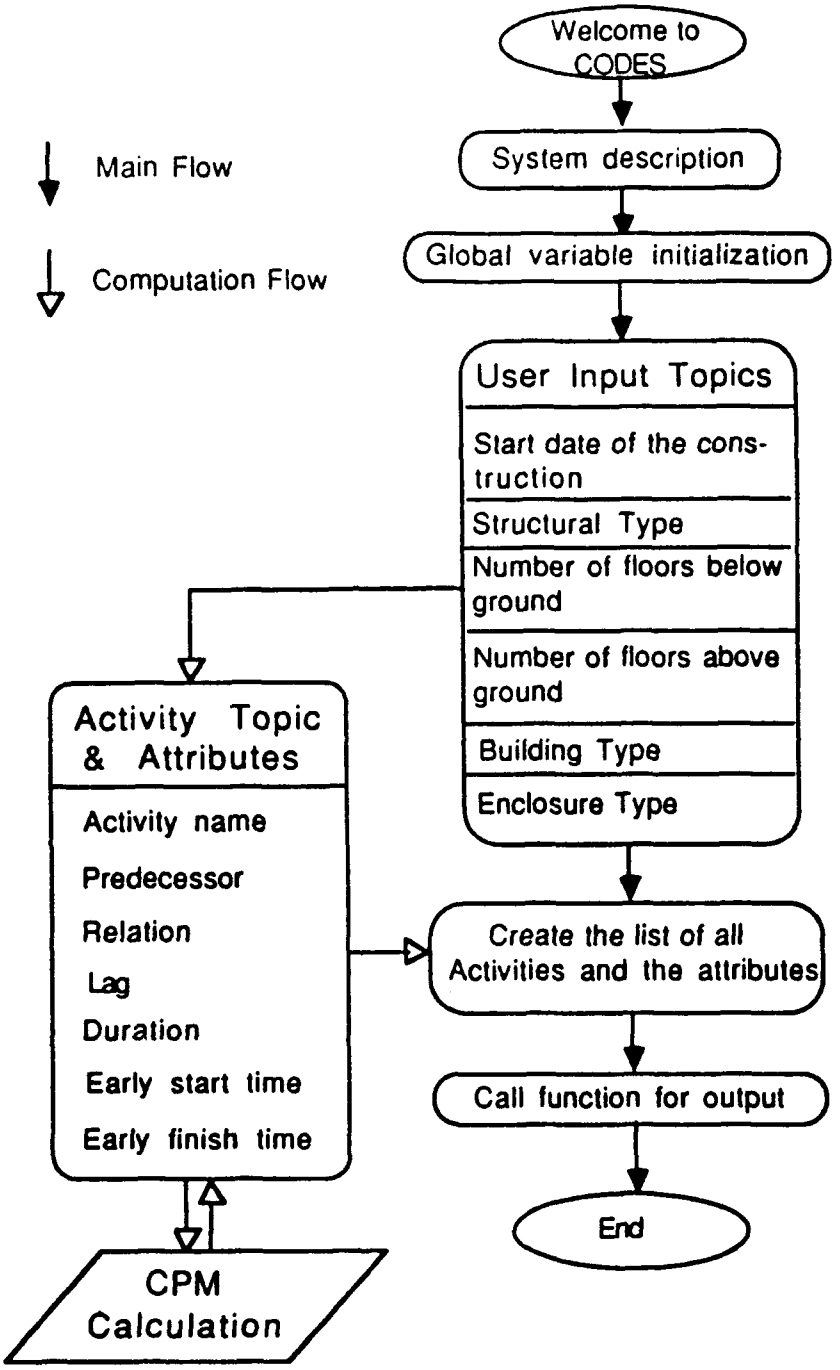

Figure 2. Flow Chart of CODES Operation.

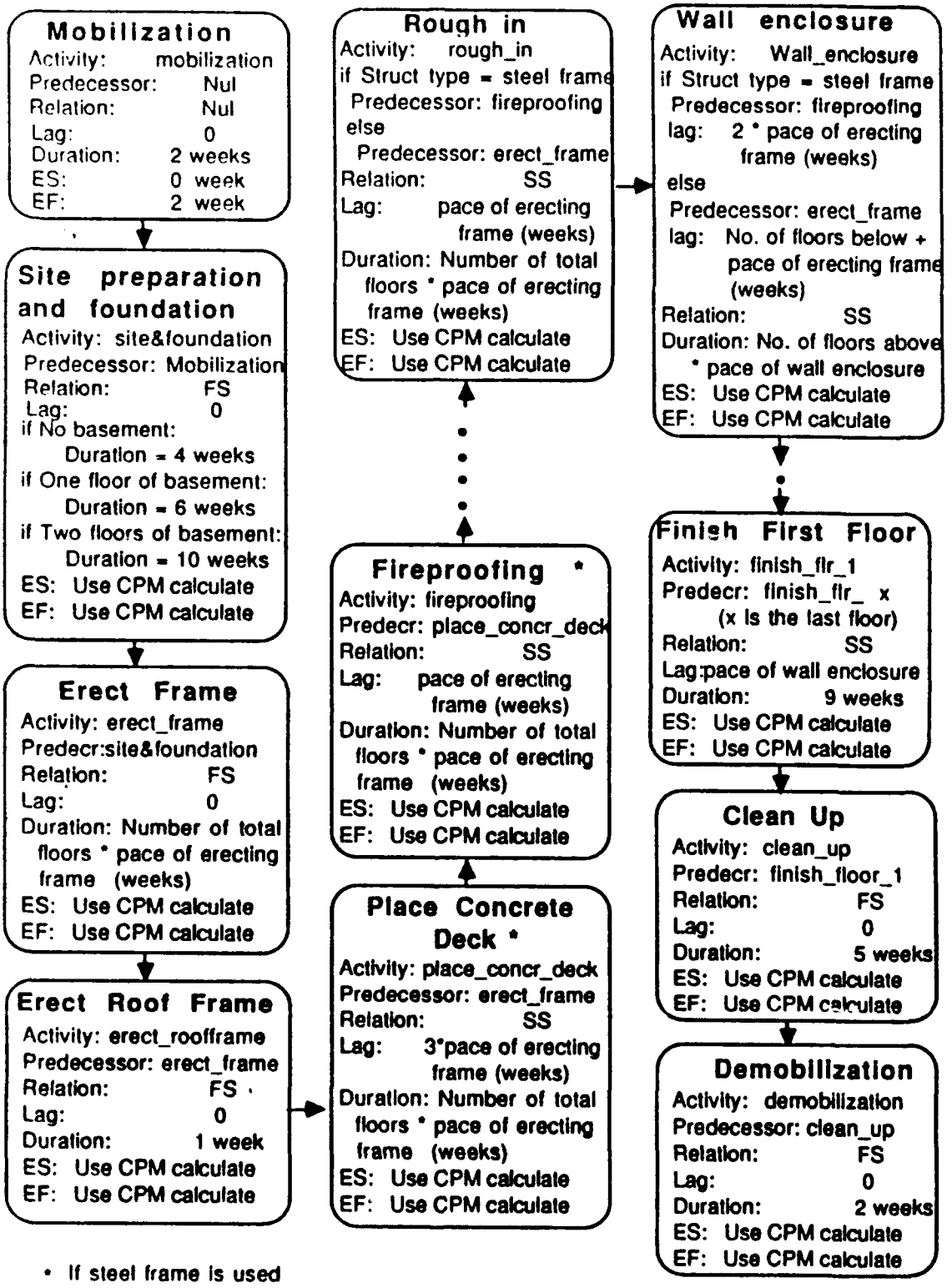

Figure 3. Activity Topics and Attributes.

Table 3

Example Run Input and Output

Step	CODES Prompt	User Response	Figure Reference
1	What kind of office are you going to build?	Office building	4
2	How many floors below ground?	1	
3	How many floors above ground?	6	
4	What type of structure?	Steel frame	
5	How many square feet of area for a typical floor area?	5000-20000	
6	What type of enclosure?	Masonry/window	
7	Amount of interior partitioning?	Highly partitioned	
8	When will the construction be started (mm/dd/yy)?	08/01/91	5
9	Which do you prefer?	Use default values in all cases	6
10	Ignore weather impact or not?	Ignore weather	7

In step 9, the user may also select "prompt user for key values." If this alternative is selected, the system displays the default parameters, which the user can then confirm or override. This alternative is discussed below.

Through a hypertext system, the user may get more information about menu terms and items. The ASK screen contains an area of highlighted text, linked to a message. If the user wants more information about the text, a press of the F4 "View" function key opens a window to display an explanatory message. If the user is already familiar with the highlighted concept, the linked information can be ignored. For example, an experienced scheduler will know the term "Procurement" and need not invoke the message. However, a trainee may need more information to understand and use the concept. The trainee merely points to "Procurement" to call for information on the topic of materials procurement for the activity under consideration. The hypertext system is transparent to the novice.

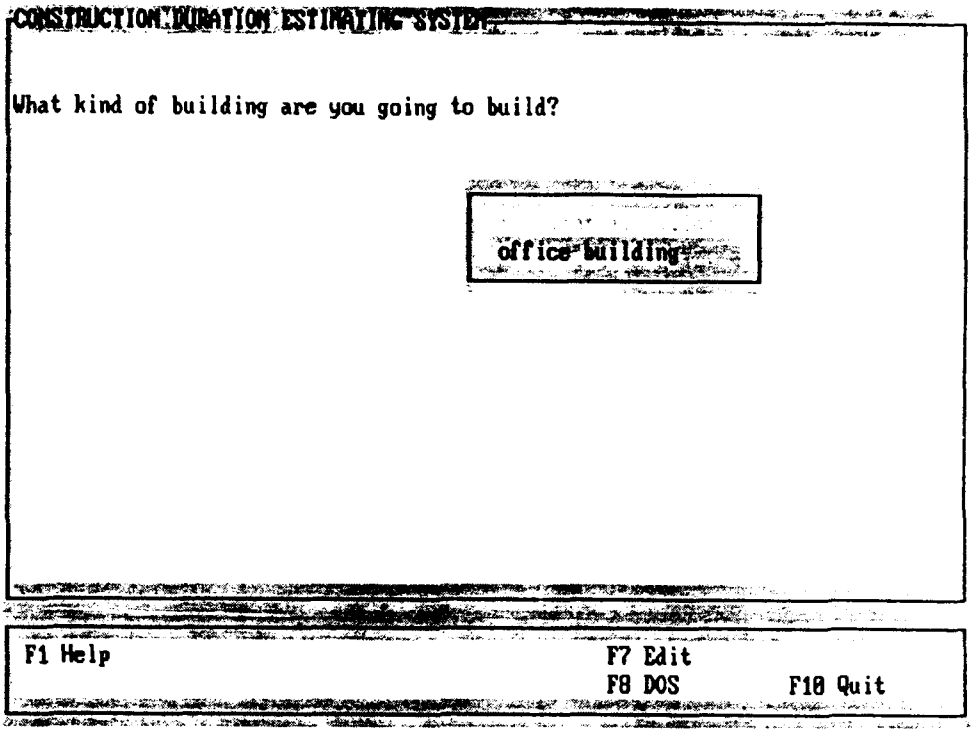

Figure 4. Building Type Prompt.

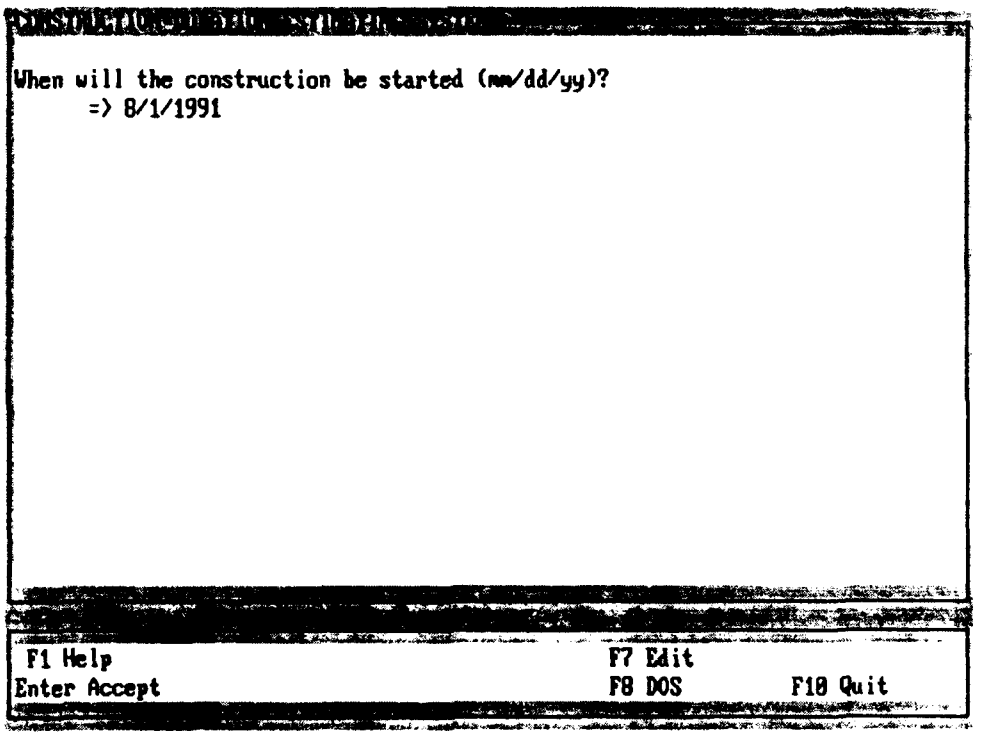

Figure 5. Construction Start Date Prompt.

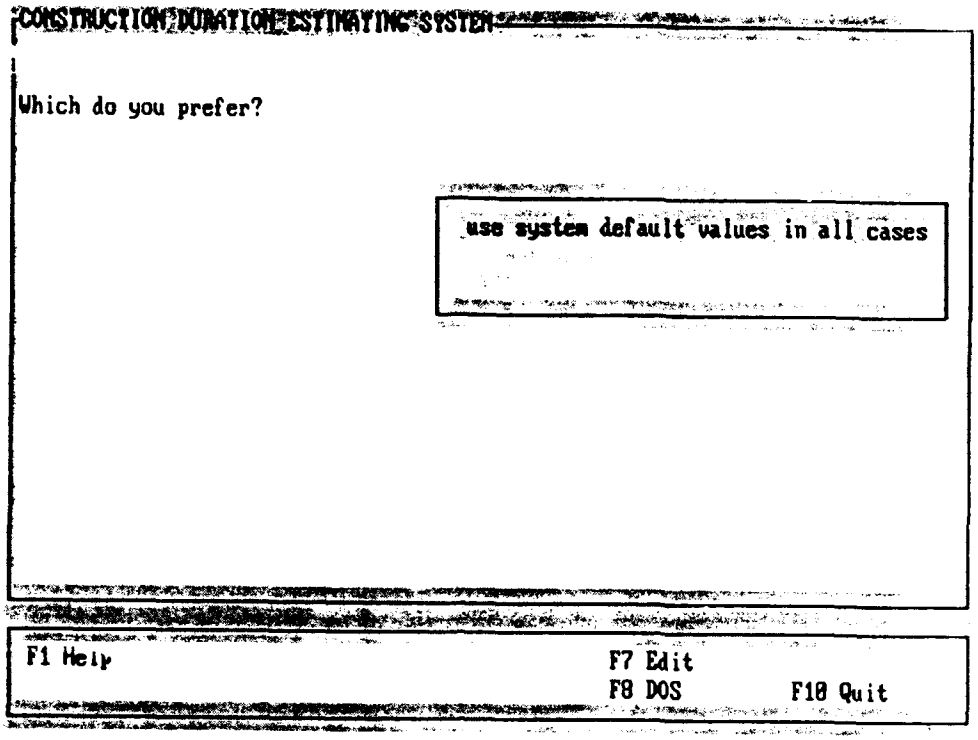

Figure 6. Prompt for Determination of User Control of System Values.

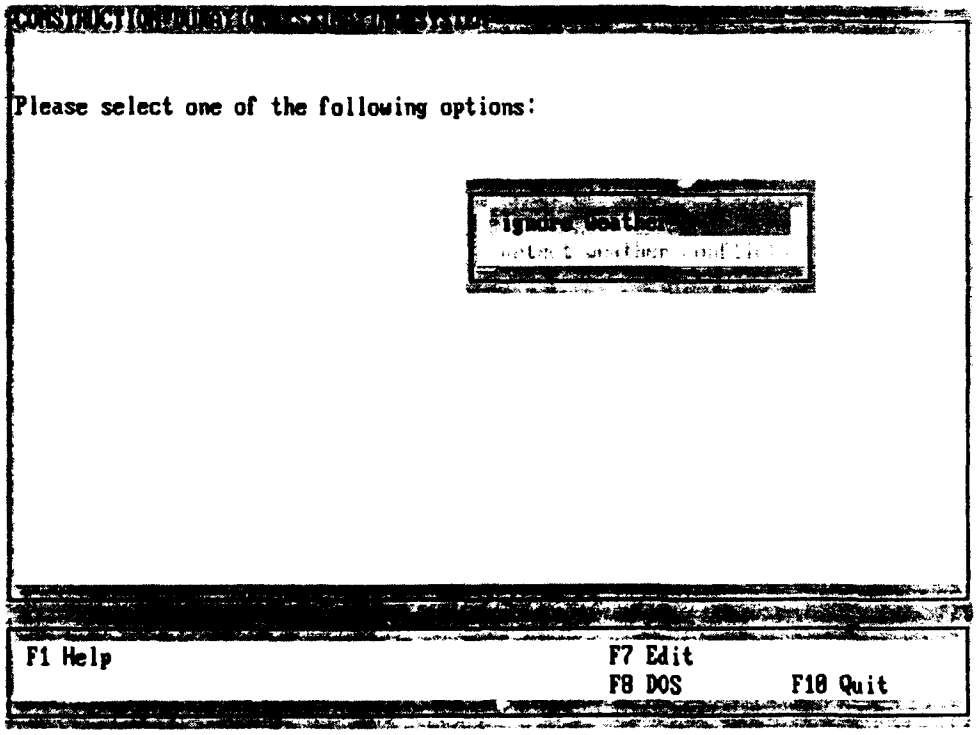

Figure 7. Prompt for Determination of Weather Considerations.

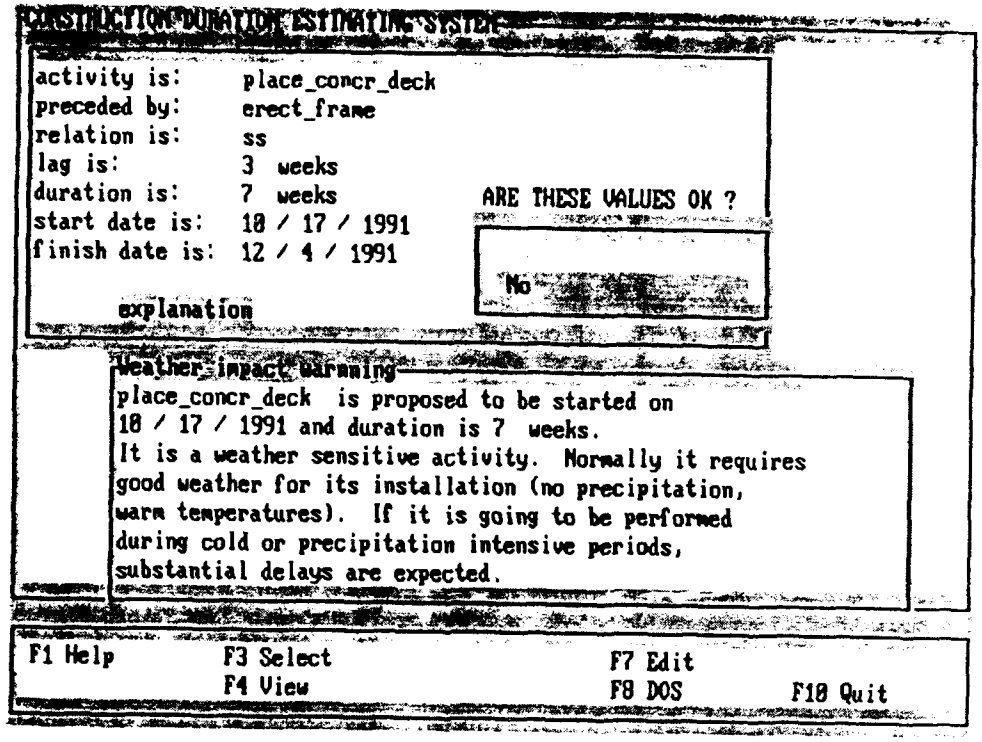

Figure 8. Weather Conflict Warning.

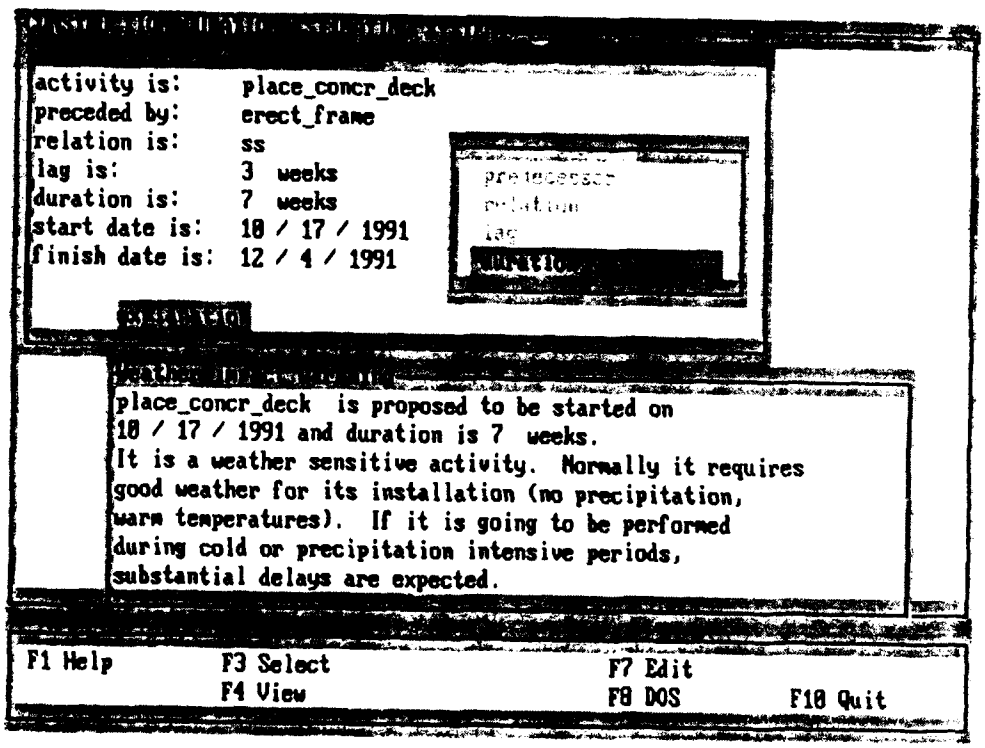

Figure 9. Parameter Selection for Value Change.

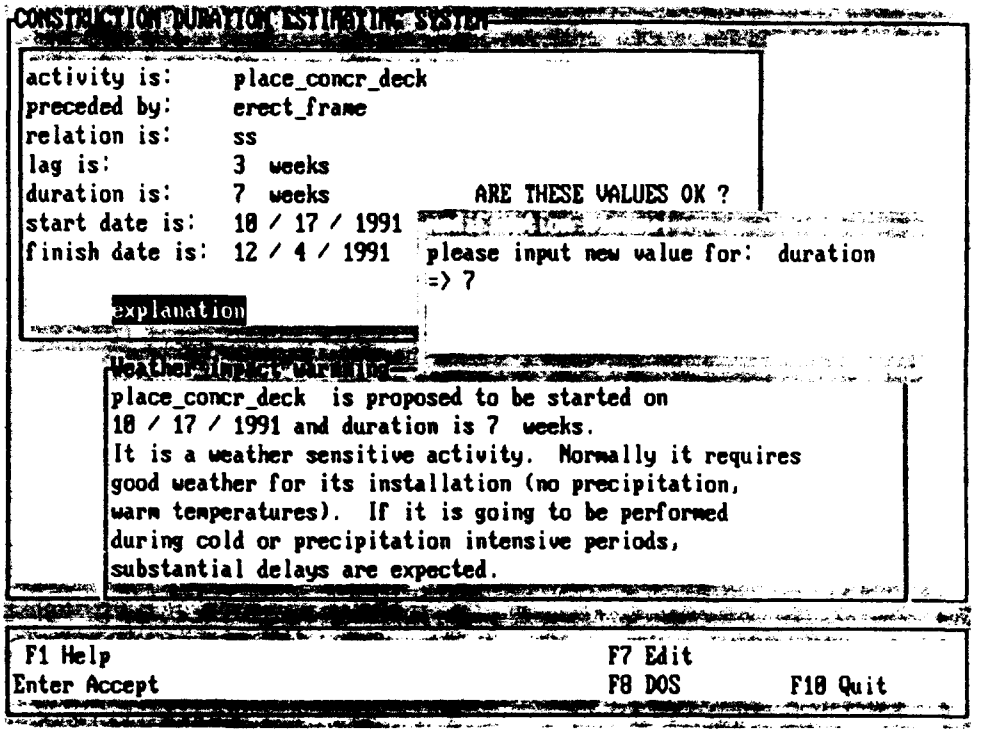

Figure 10. New Value for Selected Parameter.

After this input is completed, the system automatically processes the estimation based on the major activities discussed earlier and uses CPM to calculate the duration. The screen displays a bar chart, and both the bar chart and a text file are output to two disk files, which can be printed after processing ends (Figures 11 and 12).

After processing, the system returns to the menu illustrated in Figure 6. Here the user may also select the option to "prompt user for key values".

After the key values prompt is selected, CODES requests whether to ignore or detect weather conflicts. If the option "detect weather conflicts" is selected, the system will provide warnings related to weather constraints. (At present the system action is limited to warn of conflicts between weather-sensitive activities and expected adverse weather periods.) Figure 8 shows a weather warning that applies to the placing of concrete decks.

If the option "prompt user for key values" was selected, CODES displays on the screen the following activity characteristics: (1) activity label, (2) predecessors, (3) precedence relationship type and lag, (4) activity duration, and (5) early start and early finish. An option is available that provides additional detail on the nature of each activity and its precedence relationships. The user may also modify some of the activity characteristics (Figures 9 and 10).

Once all activities have been displayed for the user's confirmation or modification, the system displays the updated activity bar chart. It then returns to the option menu (Figure 6), allowing the user either to perform more iterations to incorporate additional activity changes or to end the session.

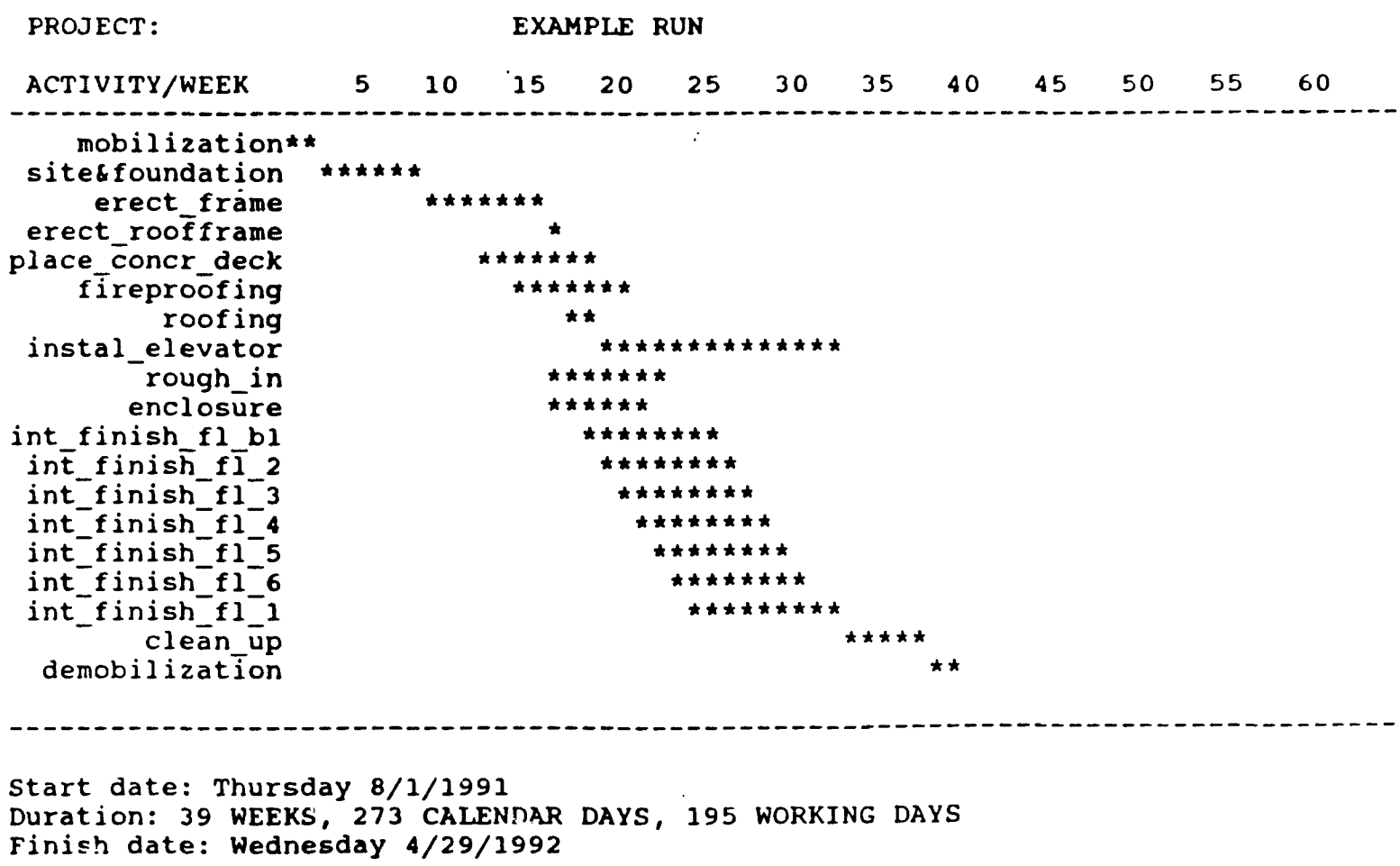

Figure 11. Bar Chart.

PROJECT: EXAMPLE RUN

ACTIVITY	PREDECESSOR	RELATION	LAG	DURATION	ES BEGINING OF WEEK x	EF END OF WEEK x
mobilization	nul	nul	0	2	1	2
site&foundation	mobilization	fs	0	6	3	8
erect_frame	site&foundation	fs	0	7	9	15
erect_roofframe	erect_frame	fs	0	1	16	16
place_concr_deck	erect_frame	ss	3	7	12	18
fireproofing	place_concr_deck	ss	2	7	14	20
roofing	erect_roofframe	fs	0	2	17	18
instal_elevator	roofing	fs	0	14	19	32
rough_in	fireproofing	ss	2	7	16	22
enclosure	fireproofing	ss	2	6	16	21
int_finish_fl_b1	enclosure	ss	2	8	18	25
int_finish_fl_2	int_finish_fl_b1	ss	1	8	19	26
int_finish_fl_3	int_finish_fl_2	ss	1	8	20	27
int_finish_fl_4	int_finish_fl_3	ss	1	8	21	28
int_finish_fl_5	int_finish_fl_4	ss	1	8	22	29
int_finish_fl_6	int_finish_fl_5	ss	1	8	23	30
int_finish_fl_1	int_finish_fl_6	ss	1	9	24	32
clean_up	int_finish_fl_1	fs	0	5	33	37
demobilization	clean_up	fs	0	2	38	39

Start date: Thursday 8/1/1991
Duration: 39 WEEKS, 273 CALENDAR DAYS, 195 WORKING DAYS
Finish date: Wednesday 4/29/1992

Figure 12. Text File.

Summary of Workshop To Review the CODES Prototype

A Workshop was conducted on 20 September 1990 with participants from different Corps of Engineers districts and the Office of Chief of Engineers. The objective of this workshop was to demonstrate the CODES prototype to a group of potential users and to invite their suggestions for improvement.

A number of comments, suggestions, and recommendations were made:

1. It was recommended that the system's scope be extended to include duration estimation of more construction project types, such as industrial buildings, hospitals, hangars, maintenance facilities, etc. It was also suggested that the system should be altered to handle multifacility projects (i.e., more than one building per project).

2. The degree of user control was welcomed by the workshop participants, but it was suggested to increase it. An important recommended feature was an option for the user to add and remove activities. It was also suggested that the program provide information about activity timing (start and end dates, plus a view of the current project bar chart) when displaying each activity for user feedback. (This recommendation has been already partially incorporated.)

3. Workshop participants agreed that an important factor in determining project duration is procurement time. It was recommended that the program incorporate procurement activities for procurement-critical items like structural steel and elevators. A procurement activity should be as long as the material/equipment takes to be delivered, and should precede the activity that installs that material/equipment.

4. Currently the prototype only warns about potential weather conflicts. It was suggested that the user be able to respond to these weather warnings by: (1) delaying the start of the activity until more favorable weather is expected, (2) extend activity duration to allow for time lost to unfavorable weather or spent in weather-protecting the operation, or (3) modify the logic of the activities to tackle nonweather-sensitive operations instead of weather-sensitive work.

5. The development of the prototype has been concurrent with other research work that assesses severe weather impact on construction operations. It was suggested to consider incorporating the results of the severe weather impact study into CODES.

6. The prototype currently handles typical construction features. However, project-specific features also affect estimating project duration. The system should also be able to address project-specific features. It was suggested that the user be given the ability to add/remove/modify the system-provided set of activities and their characteristics. In this way, the system-provided template could be tailored to fit specific project characteristics.

Several of these recommendations have already been incorporated into CODES. The start and end dates are now shown whenever a user opts to change any activity-specific information. The knowledge base was given the added capability of representing procurement constraints, by incorporating the concept of "procurement activity." A procurement activity represents the time required to acquire specific materials or equipment associated with an installation activity; so the procurement activity must logically precede the installation activity. For example, the activity "Steel Procurement" would precede the actual installation of the steel frame. Elevator Installation is now an optional activity. The user may remove this activity if the facility under analysis does not have an elevator.

4 SUMMARY

This study developed a KBS prototype (CODES) that incorporates scheduling knowledge to break down the construction phase into a set of logically sequenced major activities. Rules of thumb acquired from experienced schedulers were incorporated into CODES to estimate activity durations. The prototype system currently applies to office/residential building construction.

Using a KBS approach to forecast project construction duration is helpful to users with limited construction duration estimation knowledge. It can also be a useful tool to assist knowledgeable planners, since it expedites and provides a smart check list for duration estimation. CODES provides the ability to produce a duration estimate within minutes, and allows the incorporation of user changes that adjust the program to particular project characteristics.

This work is presently at the validation and testing stage. A program for verifying and enhancing the current CODES working prototype will be undertaken, including:

1. Hands-on review by engineering and construction district personnel to obtain direct feedback from potential users

2. A continued effort to incorporate the recommendations gained from that review and from the workshop of 20 September

3. A test of the system by applying the program to schedule records from selected building construction projects performed in the past by Corps of Engineers districts.

CITED REFERENCES

ACI Manual of Concrete Practice, Part 2: Construction Practices and Pavement; Inspection, ACI88 (American Concrete Institute, Detroit, MI, 1988).

Echeverry, Diego, *Factors for Generating Initial Construction Schedules*, Unpublished PhD Thesis (University of Illinois, Urbana, December 1990).

UNCITED REFERENCES

De La Garza, J.M., and C.W. Ibbs, *A Knowledge Engineering Approach to the Analysis and Evaluation of Schedules for Mid-Rise Construction*, Technical Report ULIU-ENG 88_2005, Construction Research series No. 23 (Department of Civil Engineering, University of Illinois, 6 June 1988).

De La Garza, J.M., C.W. Ibbs, and M.J. O'Connor, "An Expert System for Construction Schedule Analysis," *Proceedings, First Symposium on the Expert Systems in Civil Engineering* (American Society of Civil Engineers [ASCE] Spring Convention, Seattle, WA., April 1986).

Duda, R.O., *A Computer Based Consultant for Mineral Exploration*, Final Report, SRI Project 6415 (SRI International, 1979).

Fenves, S.J., "Expert Systems in Civil Engineering State of the Art," *Proceedings of the Fourth International Symposium on Robotics and Artificial Intelligence in Building Construction*, vol. 1, pp XV-XXXV (Israel Institute of Technology, Haifa, Israel, June 1987).

UNCITED REFERENCES (Cont'd)

Herbsman, Z., and Ralph Ellis, "Research of Factors Influencing Construction Productivity," *Construction Management and Economics*, vol. 8 (1990), pp. 49-61.

Levitt, R.E., and J.C. Kunz, "Using Knowledge of Construction and Project Management for Automated Schedule Updating," *Project Management Journal of the Project Management Institute*, vol. XVI, No. 5 (December 1985).

McDermott, J., *R1: A Rule-Based Configurer of Computer Systems*, Technical Report CMU-CS-80-119 (Department of Computer Science, Carnegie Mellon University, Pittsburgh, PA, 1980).

Moselhi, O., and Matthew J. Nicholas, "Hybrid Expert System for Construction Planning and Scheduling," *Journal of Construction Engineering and Management*, vol. 116, No. 2 (June, 1990), pp. 221-238.

Nomani, Zafar, Nie-jia Yau, Diego Echeverry, Amr Hassanein, and John W. Melin, *Activity Definition Index*, Working Document (Construction Engineering and Management Department, University of Illinois, Urbana, 1988).

Navinchandra, D., D. Sriram, and R.D. Logcher, "GHOST: Project Network Generator," *ASCE Journal of Construction Engineering and Management*, vol. 114, No. 3 (September 1988).

Shortliffe, E.H., "Computer-Based Medical Consultations: MYCIN," *American Elsevier* (New York, 1976).

Thompson, Beverly and William, *KnowledgePro Users Manual* (Knowledge Garden Inc., 1988).

Waterman, D.A., *A Guide to Expert Systems* (Addison-Wesley Publishing Co., 1986).

Zozaya-Gorostiza, C., and C. Hendrickson, *Knowledge-Based Planning for Construction Projects*, Technical Report No. R-88-170 (Department of Civil Engineering, Carnegie Mellon University, April 1988).

APPENDIX A: Enclosure Implementation

Figure A1 shows a flow chart for the activity Enclosure. The flow chart is explained as follows:

Determine the activity:

Activity is Enclosure.

Determine the predecessor:

If type of structure is steel frame,
then predecessor is fireproofing,
else predecessor is erect frame.

Determine the lag:

If structural type is steel frame,
then lag is 2 times the duration per floor of frame erection,
else lag is number of floors below ground plus the duration per floor of frame erection.

Determine the relation:

Relation is ss, therfore, Enclosure can only be started after the predecessor has been started.

Determine the duration per floor (pace):

If type of enclosure is glass wall,
then pace is 3 weeks per floor,
else pace is 2 weeks per floor.

If pace of enclosure is less than pace of frame erection,
then pace of enclosure is equal to pace of frame erection.

Determine the duration of Enclosure:

Duration equals the duration per floor times the number of floors above the ground.

Determine the Early Start time:

Using CPM function to calculate the Early Start time.

Determine the Early Finish time:

Early Finish time equals Early Start time plus duration.

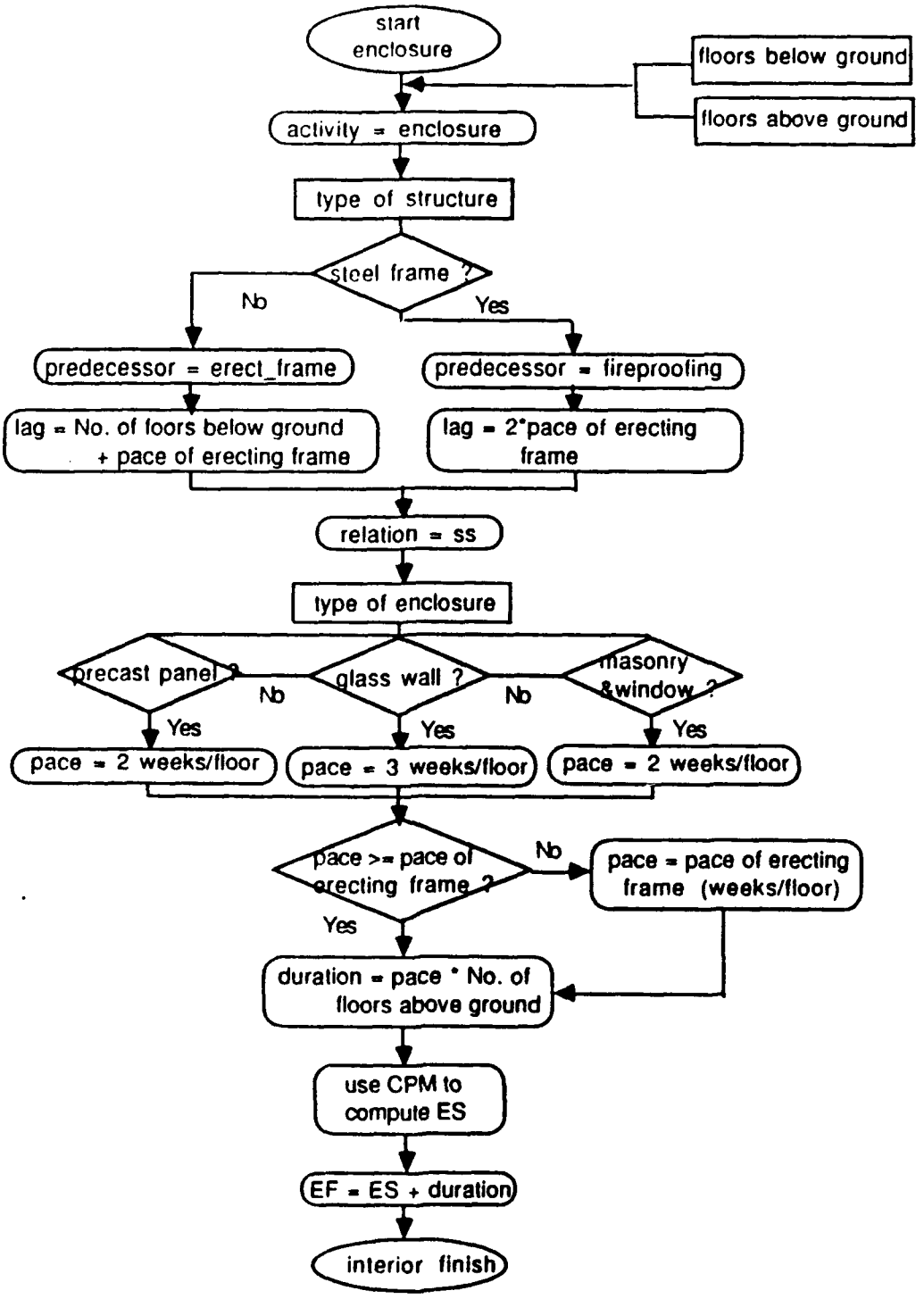

Figure A1. Flow Chart of Enclosure.

The topic Enclosure is composed of the following source code:

```
topic enclosure.
  activity is enclosure.
  if ?struct_type is 'steel frame'
    then predecessor is [fireproofing]
     and lag is ?pace * 2
    else predecessor is [erect_frame]
     and lag is ?num_floors_below + ?pace.
  relation is [ss].

  (* pace of enclosure must be >= pace of frame erection *)

  if ?enclosure_pace > ?pace
  then pace = ?enclosure_pace.

  duration is ?num_floors_above * ?pace.
  do(calc_es).
  ts is 'enclosure installation'.
  if ?option <> 1 and ?option <> 3
  then do (duration_adjustment)
  and (if ?duration mod ?num_floors_above > 0
      then pace = ?duration div ?num_floors_above + 1
      else pace = ?duration div ?num_floors_above)
  and do(calc_es).
  if ?option > 2
  then do(display_values) .
  ef = ?es + ?duration - 1.
  enclosure is [?activity,?predecessor,?relation,?lag,
              ?duration,?es,?ef].
  total_list gets ??activity.

  (* find the pace of enclosure *)
  topic enclosure_pace.
    ask('#n#nWhat #mtype of enclosure#m ?',enclosure_type,
        ['precast panels','glass wall','masonry/window']).
    If ?enclosure_type is 'glass wall'
    then pace_value is 3
    else pace_value is 2.

    (* hypertext for type of enclosure *)
    topic 'type of enclosure'.
      tf is 'explain.txt' .
      ts is 'enclosure installation' .
      (* "hypertext" is to display the text on the screen *)
      do (hypertext).
    end.

  end. (* enclosure_pace *)

end. (* enclosure *)
```

APPENDIX B: Comprehensive Code Listing

```
(* This is a prototype model of the Construction Duration Estimation
 System -- CODES *)

(* open system window *)

window('CONSTRUCTION DURATION ESTIMATING SYSTEM',white,blue,white,2,2,78,19).

(* ********************** welcome ********************** *)

  window('',white,green,yellow,12,9,55,5).

  say(#n,#x22,'WELCOME TO',
  #n,#n,#x8,'Construction Duration Estimating System ').

  close_window().

(* ****************** system description ****************** *)

  tf is 'explain.txt'.
  ts is 'description'.
  :text = read(?tf,?ts,'//').
  say(?text).
  write(con:,#e).

(* ***** initialize global variables which can be used in all topics **** *)

  activity is [].
  predecessor is [].
  relation is [].
  lag is 0.
  duration is 0.
  pace is 0.
  c_day is 0.      (* current day of a typical activity occurs *)
  c_month is 0.    (* current month of a typical activity occurs *)
  c_year is 0.     (* current year of a typical activity occurs *)
  start_m is 0.    (* start month of the project *)
  start_d is 0.    (* start day of the project *)
  start_y is 0.    (* start year of the project *)
  es is 0.         (* early start *)
  ef is 0.         (* early finish *)
  option is [].
  elevator is Yes.

  (* the name list of activities that procurement needs to be considered *)
  procurement_activities = [erect_frame,instal_elevator,enclosure].

  (* the name list of activities that modification is allowed *)

  modification_activities = [mobilization,site&foundation,erect_frame,enclosure,roofing].
```

```
(* ask the user to input topic by topic *)

 ?building_type.      (* input building type *)
 ?num_floors_below.   (* input number of floors of basement *)
 ?num_floors_above.   (* input number of floors above ground *)
 ?struct_type.        (* input structural type of the building *)
 ?floor_area.         (* input area of a typical floor *)
 ?enclosure_pace.     (* input enclosure type for enclosure_pace selection *)
 ?finishing_pace.     (* input building type and partition type for finishing_pace selection *)
 ?start_date.         (* input start date of construction *)

(* process the scheduling procedures *)

 do(project_const).

(* ****************** user input topics ****************** *)

 topic building_type.   (* input building type *)
  ask('#n#nWhat kind of building are you going to build?',building_type,
     ['residential building','office building']).
 end. (* building_type *)

 topic struct_type.     (* input structure type *)
  ask('#n#nWhat #mtype of structure#m ?',struct_type,['steel frame','cast in place concrete',masonry,other]).

  if ?struct_type = other or ?struct_type = masonry
  then do ('type of structure')
  and do (struct_type).

  topic 'type of structure'. (* print text on the screen for explanation *)
   tf is 'explain.txt'.
   ts is 'type of structure'.
   do(hypertext).
  end.
 end. (* struct_type *)

 (* input number of floors above ground and number of floors below ground and calculate the total number of      floors *)

 topic num_floors_above.
  ask('#n#nHow many stories above ground?',answer,['less than 4 stories', 4,5,6,7,8,9,10,11,12,
     'over 12 stories']).

  if ?answer is 'less than 4 stories'
  then ask('#n#nHow many stories is it?',answer,[1,2,3])
   and ask('#n#nIs there elevator?',elevator,[Yes,No]).

  if ?answer = 'over 12 stories'
  then ask('#n#nPlease input the exact number of stories.',answer,[13,14,15,16,17,18,19,20]).
  num_floors_above = ?answer.
 end.
```

```
topic num_floors_below.
  ask('#n#nHow many floors below ground?',num_floors_below,[0,1,2]).
end.

(* compute the number of total floors *)

topic num_floors_total.
  num_floors_total = ?num_floors_below + ?num_floors_above.
end.

(* input typical floor area *)

topic floor_area.
  ask('#n#nHow many square feet of area for a typical floor area?',floor_area,
     ['less than 5000','5000 - 20000','20001 - 25000','over 25000']).

  if ?floor_area = 'less than 5000'
  then tf is 'explain.txt'
   and ts is 'floor area case 1'
   and do(hypertext).

  if ?floor_area = '20001 - 25000'
  then tf is 'explain.txt'
   and ts is 'floor area case 3'
   and do(hypertext).

  if ?floor_area = 'over 25000'
  then tf is 'explain.txt' and ts is 'floor area case 4' and do(hypertext)
  and do(floor_area).
end. (* floor_area *)
(* input the date of the project to be started *)

topic start_date.
  write(con:,#e,#n).
  read_response('When will the construction be started (mm/dd/yy)?
   #s',temp).
  start_date is string_to_list(?temp,'/'). (* change string into list *)
  start_m is first(?start_date).          (* get the start month *)
  start_d is element(?start_date,2).      (* get the start day   *)
  start_y is last(?start_date).           (* get the start year  *)

  (* if user inputs two figures for the start year, change it into four figures *)

  ly = string_length (?start_y).
  if ?ly <> 4
  then (if ?ly = 2
        then (if ?start_y <80
              then start_y = ?start_y + 2000
              else start_y = ?start_y + 1900)
        else write(con:,#n,'invalid date')
         and do(start_date)).
```

```
(* check if the user input of start date is valid. Start year should be greater than 1980, start month should be greater or
equal to 1 and less or equal to 12, start date should meet the requirement of each month, such as in January, it should be
greater or equal to 1 and less or equal to 31. *)

  if ?start_y < 1980 or ?start_m < 1 or ?start_m > 12
  then write(con:,#n,'invalid date')
  and do(start_date).

  if one_of([1,3,5,7,8,10,12],?start_m)
  then (if ?start_d > 31 or ?start_d < 1
       then write(con:,#n,'invalid date')
        and do(start_date)).
  if one_of([4,6,9,11],?start_m)
  then (if ?start_d > 30 or ?start_d < 1
       then write(con:,#n,'invalid date')
        and do(start_date)).

  if ?start_m is 2
  then (if ?start_y mod 4 > 0
       then (if ?start_d > 28 or ?start_d < 1
            then write(con:,#n,'invalid date')
             and do(start_date))
       else (if ?start_d > 29 or ?start_d < 1
            then write(con:,#n,'invalid date')
             and do(start_date))).

  (* check weather impact on constructions and remind user that winter is probably not good for site preparation and
foundation activities *)

      if ?start_m < 3 or ?start_m > 9
      then write(con:,#n,'The #mweather#m is not favorable for site preparation and foundation activities.
              #nWould you like to change the starting date?')
       and move_cursor(50,8)
       and menu(answer,[Yes,No])
       and (if ?answer is No
          then do(start_date)).

 end. (* start_date *)

 (* find interior finishing pace based on the type of partitions.
   residential building: finishing_pace = 8 weeks/floor
   office building, highly partitioned: finishing_pace = 8 weeks/floor
                moderately partitioned: finishing_pace = 5 weeks/floor *)

 topic finishing_pace.
   if ?building_type = 'residential building'
   then finishing_pace is 8
   else ask('#n#nAmount of interior partitioning ?',answer,['highly partitioned','moderately partitioned'])
   and (if ?answer = 'highly partitioned'
       then finishing_pace is 8
       else finishing_pace is 5).
 end. (* finishing_pace *)
```

```
(* find enclosure pace based on the type of enclosure.
   precast panels: enclosure_pace = 2 weeks/floor
   glass wall:     enclosure_pace = 3 weeks/floor
   masonry/window: enclosure_pace = 2 weeks/floor *)

topic enclosure_pace.
  ask('#n#nWhat #mtype of enclosure#m ?',enclosure_type,['precast panels','glass wall','masonry/window']).
  If ?enclosure_type is 'glass wall'
  then pace_value is 3
  else pace_value is 2.

  topic 'type of enclosure'.    (* hypertext for type of enclosure *)
    tf is 'explain.txt' .
    ts is 'enclosure installation' .
    do (hypertext) .
  end.

end. (* enclosure_pace *)

(* ********************** functions ********************** *)

(* calculate the proposed date to start the activity and point out the related procurement *)

topic procurement.

  (* open procurement window *)

  window('procurement',white,green,yellow,23,9,55,9).

  (* print on the screen the processing massage *)

  do(wait).

  (* compute the proposed start date of the activity *)

  prop_date is find_date_es(combine(?start_m,?start_d,?start_y,?es)).
  c_month is first(?prop_date).    (* find current month *)
  c_day is element(?prop_date,2).  (* find current day *)
  c_year is last(?prop_date).      (* find current year *)

  (* print on the screen the procurement message *)

  :text = read('procure.txt','procurement','//').
  write(con:,#e,?text).

  (* print on the screen the proposed date *)

  write(con:,#n,'The proposed date to start this activity is:').
  write(con:,#n,'#s',?c_month,'/',?c_day,'/',?c_year,#n).

  (* print on the screen the text of procurement, ts is related with activity *)
```

```
  :text = read('procure.txt',?ts,'//').
  write(con:,?text).
  write(con:,#w).
  close_window().
end. (* procurement *)

(* hypertext of explanation for general use *)

topic hypertext.
  window('explanation',white,green,yellow,23,9,55,7).
  :text = read(?tf,?ts,'//').
  say(?text).
  close_window().
end. (* hypertext *)

(* ********** Messages ********** *)

(* print the processing message *)

topic wait.
 write(con:,#e,#x15,#y9,'One moment, processing...').
end. (* wait *)

(* print on the screen the explanation for weather impact *)

topic weather.
  ts is 'Weather'.
  do(hypertext).
end.

(* print weather impact message on the screen *)

topic duration_message.
  window('',white,green,yellow,14,9,60,8).
  write(con:,'#s',?activity,' is proposed to be started on ',#n).
  write(con:,'#s',?c_month,'/',?c_day,'/',?c_year,'and duration is').
  write(con:,'#s',?duration,' weeks.',#n).
  tf = 'explain.txt'.
  :text = read(?tf,'Weather-duration','//').
  write(con:,?text).
  write(con:,#w).
  close_window().
end. (* duration_message *)

(* ********** main program ********** *)

topic project_const.

  (* ask user for options: process straight - process without user interface and weather impact
                           process with weather impact *)
```

```
answer = [].
while ?answer <> EXIT
then (if ?option > 0
   then reset(total_list)
   and output(combine(?total_list,?start_m,?start_d,?start_y)))
and ask('#n#nWhich do you prefer?',answer,
      ['use system default values in all cases',
      'prompt user for key values',EXIT])
and (if ?answer <> EXIT
   then ask('#n#nPlease select one of the following options:',
   answer2,['ignore weather','detect weather conflicts'])
   and (if ?answer = 'use system default values in all cases'
    then (if ?answer2 = 'ignore weather'
       then option = 1
       else option = 0
       and say('#nSorry, this option is not available at present time.')
       and answer = [])
    else (if ?answer2 = 'ignore weather'
       then option = 3
       else ask('#nPlease select one of the following duration estimating options:',answer2,
            ['detect weather conflicts and warn with no action',
             'detect weather conflicts and modify duration accordingly'])
       and (if ?answer2 = 'detect weather conflicts and warn with no action'
          then option = 4
          else option = 0
          and answer = []
          and say('#nSorry, this option is not available at present time.'))))).

(* print on the screen the end message *)

say(#n#n,'This is the end of CODES, please find the chart and text output
   files at OUTCHART.TXT and OUTTEXT.TXT.').

(* get the total list of activities *)

topic total_list.

 (* form a name list of activities *)

 name_list is[mobilization, site&foundation, erect_frame, erect_roofframe, place_concr_deck,
 fireproofing, roofing, instal_elevator, rough_in, enclosure].

 if ?elevator = No
 then name_list is remove(?name_list,instal_elevator).

 (* process the activities on name_list *)

 list is ?name_list.
 while ?list <> []
  then ?first(?list)
  and list is rest(?list).
```

```
topic mobilization.
  activity is mobilization.     (* assign activity name *)
  predecessor is nul.           (* assign predecessors name *)
  relation is nul.              (* assign relations list *)
  lag is 0.                     (* get lag value *)
  duration is 2.                (* get duration value *)
  ts is 'mobilization' .        (* assign explanation text *)
  es = 1.                       (* compute early start time *)
  ef = 2.                       (* compute early finish time *)
  if ?option > 2                (* if option > 2  *)
  then do (display_values) .    (* display values of the activity *)

  (* form a list for the activity *)

  mobilization is [?activity,?predecessor,?relation,?lag,?duration,?es,?ef].

  (* attach the activity list to the total_list *)

  total_list gets ??activity.
end. (* mobilization *)

topic site&foundation.

  activity is site&foundation.  (* assign activity name *)
  predecessor is [mobilization].     (* assign predecessor list *)
  relation is [fs].             (* assign relation type list *)
  lag is 0.                     (* get lag value *)

  if ?num_floors_below = 0
  then duration is 4            (* no basement, duration = 4 *)
 else (if ?num_floors_below = 1 (* one floor of basement,duration = 6 *)
       then duration is 6    (* two floors of basement,duration = 10 *)
       else duration is 10).

  do(cpm_calc).                 (* compute early start time *)
  ts is 'site and foundation'.  (* assign explanation text *)
  if ?option > 2                (* if flag = 0, there is no display of *)
  then do (display_values) .    (* values *)

  (* get the activity value list *)
  site&foundation is
        [?activity,?predecessor,?relation,?lag,?duration,?es,?ef].

  (* attach the value list to the total list *)

  total_list gets ??activity.
end. (* site&foundation *)

topic erect_frame.

(* if structure type is not steel frame, then there are no concrete
   deck installation and fireproofing activities *)
```

```
  if ?struct_type <> 'steel frame'
  then name_list is remove(?name_list,[place_concr_deck,fireproofing])
   and list is remove(?list,[place_concr_deck,fireproofing]).

  activity is erect_frame.          (* assign activity name *)
  predecessor is [site&foundation]. (* assign predecessor name list *)
  relation is [fs].                 (* assign relation type list *)
  lag is 0.                         (* get lag *)
  pace is 1.                        (* assign default value of pace *)
  duration is ?num_floors_total * ?pace. (* compute duration *)
  do(cpm_calc).                     (* compute early start time *)
  ts is 'frame erection' .          (* assign the explanation text *)
  if ?option > 2
  then do (display_values) .

  (* get the activity value list *)

  erect_frame is
          [?activity,?predecessor,?relation,?lag,?duration,?es,?ef].

  (* attach the value list to the total_list *)

  total_list gets ??activity.
end. (* erect_frame *)

topic erect_roofframe.

  activity is erect_roofframe.      (* assign activity name *)
  predecessor is [erect_frame].     (* assign predecessor name list *)
  relation is [fs].                 (* assign relation type list *)
  lag is 0.                         (* get lag *)
  duration is 1.                    (* assign duration *)
  do(cpm_calc).                     (* compute early start time *)
  ts is 'roof frame erection'.      (* assign the explanation text *)
  if ?option > 2
  then do (display_values).

  (* get the activity value list *)

  erect_roofframe is
          [?activity,?predecessor,?relation,?lag,?duration,?es,?ef].

  (* attach the value list to the total_list *)

  total_list gets ??activity.
end. (* erect_roofframe *)

topic place_concr_deck.
  activity is place_concr_deck.
  predecessor is [erect_frame].
  relation is [ss].
  lag is ?pace * 3.
```

```
  duration is ?num_floors_total * ?pace.
  do(cpm_calc).
  ts is 'install concrete deck'.

  if ?option <> 1 and ?option <> 3
  then do (duration_adjustment)
  and do(cpm_calc).

  if ?option > 2
  then do (display_values) .
  place_concr_deck is
       [?activity,?predecessor,?relation,?lag,?duration,?es,?ef].
  total_list gets ??activity.
end. (* place_concr_deck *)

topic fireproofing.
  activity is fireproofing.
  predecessor is [place_concr_deck].
  relation is [ss].
  lag is ?pace * 2.
  duration is ?num_floors_total * ?pace.
  do(cpm_calc).
  ts is 'fire proofing' .
  if ?option <> 1 and ?option <> 3
  then do (duration_adjustment)
  and do(cpm_calc).
  if ?option > 2
  then do (display_values).
  fireproofing is
       [?activity,?predecessor,?relation,?lag,?duration,?es,?ef].
  total_list gets ??activity.
end.  (* fireproofing *)

topic roofing.
  activity is roofing.
  predecessor is [erect_roofframe].
  relation is [fs].
  lag is 0.
  duration is 2.
  do(cpm_calc).
  ts is 'Roofing' .
  if ?option <> 1 and ?option <> 3
  then do (duration_adjustment)
  and do(cpm_calc).
  if ?option > 2
  then do (display_values) .
  roofing is [?activity,?predecessor,?relation,?lag,?duration,?es,?ef].
  total_list gets ??activity.
end. (* roofing *)
```

```
topic instal_elevator.
  activity is instal_elevator.
  predecessor is [roofing].
  relation is [fs].
  lag is 0.
  duration is 12.
  do(cpm_calc).
  ts is 'elevator installation' .
  if ?option > 2
  then do(display_values) .
  instal_elevator is
          [?activity,?predecessor,?relation,?lag,?duration,?es,?ef].
  total_list gets ??activity.
end. (* instal_elevator *)

topic rough_in.
  activity is rough_in.
  if ?struct_type is 'steel frame'
    then predecessor is [fireproofing]
    else predecessor is [erect_frame].
  relation is [ss].
  lag is ?pace * 2.
  duration is ?num_floors_total * ?pace.
  do(cpm_calc).
  ts is 'rough in' .
  if ?option > 2
  then do (display_values) .
  rough_in is[?activity,?predecessor,?relation,?lag,?duration,?es,?ef].
  total_list gets ??activity.
end. (* rough_in *)

topic enclosure.
  activity is enclosure.
  if ?struct_type is 'steel frame'
    then predecessor is [fireproofing]
     and lag is ?pace * 2
    else predecessor is [erect_frame]
     and lag is ?num_floors_below + ?pace.
  relation is [ss].

(* pace of enclosure must be >= pace of frame erection *)

  if ?enclosure_pace > ?pace
  then pace = ?enclosure_pace.

  duration is ?num_floors_above * ?pace.
  do(cpm_calc).
  ts is 'enclosure installation'.
  if ?option <> 1 and ?option <> 3
  then do (duration_adjustment)
  and (if ?duration mod ?num_floors_above > 0
      then pace = ?duration div ?num_floors_above + 1
```

```
      else pace = ?duration div ?num_floors_above)
   and do(cpm_calc).
   if ?option > 2
   then do(display_values) .
   enclosure is[?activity,?predecessor,?relation,?lag,?duration,?es,?ef].
   total_list gets ??activity.
end. (* enclosure *)

(* create topics for interior finishing of basement *)

   (* explanation text starts at 'Interior finishing' *)

   ts is 'Interior finishing'.

   (* if number of floors below ground great than 0, create topic
     for each floor finishing starting from the lowest floor *)

   if ?num_floors_below > 0
   then nf is ?num_floors_below
    and (while ?nf <> 0
        then do(wait)
        (* form activity name *)
        and activity is concat(int_finish_fl_b,?nf)
        and j = ?nf + 1              (* recall predecessor *)

   (* predecessor is enclosure for the lowest floor and nf + 1 floor for

     the rest floors. The counting starts from the ground, and the
     floor number increases as it is deeper *)

        and (if ?nf = ?num_floors_below
            then predecessor is [enclosure]
            else predecessor is concat(int_finish_fl_b,?j))
        and relation is ss

   (* lag = 2 * pace of frame erection for the lowest floor and
     lag = pace of frame erection for the rest floors *)

        and (if ?nf = ?num_floors_below
            then lag is ?pace * 2
            else lag is ?pace)

   (* duration is finishing pace which depends on the type of building
     and the type of partition *)

        and duration is ?finishing_pace

     (* calculate early start time *)

        and do(cpm_calc)
```

```
(* display the values of the lowest floor to the user.  there is no
   display for other floors except the first floor *)

      and (if ?nf = ?num_floors_below and ?option > 2
          then do(display_values))

   (* calculate the early finish time *)


   (* assign the value list to the new created topic *)

      and concat(int_finish_fl_b,?nf) is [?activity,?predecessor,
                                ?relation,?lag,?duration,?es,?ef]

   (* attach the new list to total_list *)

      and total_list gets ??activity

   (* prepare the next loop *)

      and nf is ?nf - 1).

 (* create topic for floor finishing, see above for comments *)

 nf is 2.
 while ?nf <= ?num_floors_above
 then do(wait)
  and activity is concat(int_finish_fl_,?nf)
  and j = ?nf - 1
  and (if ?nf = 2
      then (if ?num_floors_below > 0
          then predecessor is [int_finish_fl_b1]
          else predecessor is [enclosure])
      else predecessor is concat(int_finish_fl_,?j))
  and relation is ss
  and (if ?nf = 2
      then (if ?num_floors_below > 0
           then lag is ?pace
           else lag is ?pace * 2)
      else lag is ?pace)
  and duration is ?finishing_pace
  and do(cpm_calc)
  and (if ?nf = 2 and ?option > 2
      then do(display_values))
  and concat(int_finish_fl_,?nf) is [?activity,?predecessor,?relation,
                                ?lag,?duration,?es,?ef]
  and total_list gets ??activity
  and nf is ?nf + 1.

(* get the values of the last two activities *)

list is [int_finish_fl_1,clean_up,de_mobilization].
```

```
while ?list <> []
 then ?first(?list)
  and list is rest(?list).

topic int_finish_fl_1.
  activity is int_finish_fl_1.

(* if number of total stories is greater than 1, predecessor is interior
   finishing, else predecessor is enclosure. If number of floors above
   ground is greater than 1, predecessor is the highest floor finishing,
   else predecessor is the first basement floor finishing *)

  if ?num_floors_total > 1
   then (if ?num_floors_above > 1
        then predecessor is [concat(int_finish_fl_,?num_floors_above)]
        else predecessor is [int_finish_fl_b1])
   else predecessor is [enclosure].

  relation is [ss].
  if ?num_floors_total > 1
   then lag is ?pace
   else lag is ?pace * 2.
  duration is 9.
  do(cpm_calc).
  ts is 'Interior finishing' .
  if ?option > 2
  then do (display_values) .

  if ?elevator = Yes
  then do(ef_adjustment).

  int_finish_fl_1 is
        [?activity,?predecessor,?relation,?lag,?duration,?es,?ef].
  total_list gets ??activity.

(* find the ef position of elevator installation on the total list in
   order to replace the value *)

   topic ef_adjustment.

     if ?struct_type <> 'steel frame'
     then elevator_ef_location = 42
     else elevator_ef_location = 56.
     ef_elevator = element(?instal_elevator,7).

(* instal_elevator duration adjustment. compare the ef time and
   assign the later ef to both instal_elevator and int_finish_fl_1 *)

     if ?ef > ?ef_elevator
     then elevator_d = ?ef - element(?total_list,
                                ?elevator_ef_location - 1) + 1
```

```
    and total_list = replace_elements(?total_list,
                [?elevator_ef_location - 2,?elevator_ef_location],
                [?elevator_d,?ef])
   else ef = ?ef_elevator
    and duration = ?ef - ?es + 1.
  end. (* ef_adjustment *)
end. (* int_finish_fl_1 *)

topic clean_up.
  activity is clean_up.
  predecessor is [int_finish_fl_1].
  relation is [fs].
  lag is 0.
  duration is 5.
  do(cpm_calc).
  ts is 'clean up' .
  if ?option > 2
  then do (display_values) .
  clean_up is [?activity,?predecessor,?relation,?lag,?duration,?es,?ef].
  total_list gets ??activity.
end. (* clean_up *)

topic de_mobilization.
  activity is de_mobilization.
  predecessor is [clean_up].
  relation is [fs].
  lag is 0.
  duration is 2.
  do(cpm_calc).
  ts is 'de_mobilization'.
  if ?option > 2
  then do (display_values) .
  de_mobilization is
          [?activity,?predecessor,?relation,?lag,?duration,?es,?ef].
  total_list gets ??activity.
end. (* de_mobilization *)

(* print on the screen the explanation for different activity *)

topic explanation.
 window('explanation',white,green,yellow,23,9,55,7).
 write(con:,'Activity#s',?activity,'is preceded by',?predecessor).
 write(con:,#n,'and#s',?activity,'is going to be performed after',#n).
 write(con:,'#s',?predecessor,'has been').
 if ?relation is ss
 then write(con:,'started (ss). The time',#n,'delay from start of')
 else write(con:,'finished (fs). The time',#n,'delay from finish of').
 write(con:,'#s',?predecessor,'to start of',#n,?activity).
 write(con:,'is#s',?lag,'weeks. To complete this activity ').
 write(con:,#n,'#s',?duration,'weeks of duration are needed.').
 write(con:,#n,'          #fyellow <space bar for more message> #d',#w).
 :text = read(?tf,?ts,'//').
```

```
  say(?text).
  close_window().
end. (* explanation *)

(* the main topic that dominates the display and modification procedures *)

topic display_values.
  write(con:,#e).                          (* clean the screen *)
  window('',white,green,yellow,3,4,60,10).   (* open the display window *)
  do(display_current_values).
  write(con:,#n#n,'       #mexplanation#m'). (* hypertext of explanation *)
  if one_of(?procurement_activities,?activity) (* hypertext of procurement *)
    or string_where(?activity,'finish') > 0
    then write(con:,#n,'       #mprocurement#m').

  (* allow user to modify values of activities of frame erection and
     enclosure, the value of pace will dominate the values of lag and
     duration of the following activities *)

   write(con:,#x38,#y5,'#fyellow ARE THESE VALUES #fblink OK ?#d').
   move_cursor(38,7).
   menu(answer,[Yes,No]).

   if ?answer is No    (* if answer is NO, then do modification *)
   then do(user_modify)
   else close_window().
end. (* display_values *)

(* display the current activity values *)

topic display_current_values.

  write(con:,#e,'activity is:    #s',?activity).
  write(con:,#n,'preceded by:    #s',?predecessor).
  write(con:,#n,'relation is:    #s',?relation).
  write(con:,#n,'lag is:         #s',?lag,' weeks').
  write(con:,#n,'duration is:    #s',?duration,' weeks').
  do(display_start_date).
  do(display_end_date).

  topic display_end_date.

  (* compute the proposed finish date of the activity *)

   prop_date is find_date_ef(combine(?start_m,?start_d,?start_y,?ef)).
   c_month is first(?prop_date).    (* find current month *)
   c_day is element(?prop_date,2).  (* find current day *)
   c_year is last(?prop_date).      (* find current year *)
   write(con:,#n,'finish date is: #s',?c_month,'/',?c_day,'/',?c_year).

  end. (* display_end_date *)
```

```
  topic display_start_date.

   (* compute the proposed start date of the activity *)

   prop_date is find_date_es(combine(?start_m,?start_d,?start_y,?es)).
   c_month is first(?prop_date).    (* find current month *)
   c_day is element(?prop_date,2).  (* find current day *)
   c_year is last(?prop_date).      (* find current year *)
   write(con:,#n,'start date is:  #s',?c_month,'/',?c_day,'/',?c_year).

  end. (* display_start_date *)

end. (* display_current_values *)
(* allow user to modify the values of relation, lag, duration or pace *)

topic user_modify.
  move_cursor(39,4).

  (* for activities erect_frame and enclosure, allow user to modify
     pace, for others, allow user to modify duration *)

  answer = [].
  if ?activity = erect_frame or ?activity = enclosure
  then 'duration/per floor' = ?pace
  and menu(answer,[predecessor,relation,lag,'duration/per floor'])
  else menu(answer,[predecessor,relation,lag,duration]).

  (* if answer is not nul, display the values have been modified,
     otherwise, open a window and read_response from user *)

   window('modification window',white,yellow,red,39,9,40,4).
   write(con:,'please input new value for: #s',?answer).
   read_response(#n,?answer,??answer).
   close_window().

   (* compute the durations of erect_frame and enclosure *)

   if ?answer is 'duration/per floor'
   then (if ?activity = erect_frame
         then duration = ?num_floors_total * ??answer
         else duration = ?num_floors_above * ??answer).

   (* After modification is done, display the values modified *)
   if ?activity = mobilization
   then ef = ?es + ?duration - 1
   else do(cpm_calc).
   do(modify_done).
end. (* user_modify *)

(* display the values after modification *)
```

```
topic modify_done.
  do(display_current_values).
  write(con:,#x38,#y4,'#fyellow ARE THESE VALUES #fblink OK #d?').
  move_cursor(38,6).
  menu(answer,[Yes,No]).
  if ?answer is No
   then do(user_modify)
   else close_window().
end. (* modify_done *)
(* check the starting or finishing month of an activity for the sake
   of weather impact. for the time being, there is no action involved *)

topic duration_adjustment.

  (* compute the proposed date of activity to be started *)

  prop_date is find_date_es(combine(?start_m,?start_d,?start_y,?es)).
  c_month is first(?prop_date).      (* get the proposed month *)
  c_day is element(?prop_date,2).    (* get the proposed day *)
  c_year is last(?prop_date).        (* get the proposed year *)

  if ?c_month > 11 or ?c_month < 3   (* check winter time for es *)
  then (if ?option > 2
       then (if ?option > 3
            then do(duration_message))    (* give a warning message *)
       and (if ?option <> 4
           then do(duration_extend(?c_month)))) (* extend the duration *)
  else temp = ?es + ?duration         (* check winter time for ef *)
   and prop_date is find_date_ef(combine(?start_m,?start_d,?start_y,?temp))
   and (if first (?prop_date) > 11 or first (?prop_date) < 3
      then (if ?option > 2
           then (if ?option > 3
                then do(duration_message))    (* give a warning message *)
            and (if ?option <> 4
           then do(duration_extend(?c_month))))). (* extend the duration *)

  topic duration_extend(mm).
    if ?mm = 12
    then duration = ?duration + 10
    else (if ?mm = 1
         then duration = ?duration + 6
         else duration = ?duration + 2).
  end. (* duration_extend *)
end. (* duration_adjustment *)

(* ********************** CPM ************************ *)

   topic cpm_calc.

   (* display the processing message *)
     do(wait).
```

```
    var = 0.
    temp = 0.
    es = 0.
    ef = 0.
    pred_list is ?predecessor.
    type_list is ?relation.
    lag_list is ?lag.

  (* if predecessor list is not empty, continue the process *)

    while ?pred_list <> []

  (* get the name of predecessor and relation type *)

     then pred_v is first(?pred_list)
      and type_v is first(?type_list)
      and lag_v is first(?lag_list)

  (* if relation is ss, es is lag + es of predecessor
     if relation is fs, es is lag + ef of predecessor
     if relation is ff, ef is lag + ef of predecessor *)

      and (if ?type_v is ss
          then temp = element(??pred_v,6) + ?lag_v)
      and (if ?type_v is fs
          then temp = element(??pred_v,7) + ?lag_v + 1)
      and (if ?type_v is ff
          then var = element(??pred_v,7) + ?lag_v)
      and (if ?temp > ?es
          then es = ?temp
          and ef = ?es + ?duration - 1)
      and (if ?var > ?ef
          then ef = ?var
          and es = ?ef - ?duration + 1)

      and type_list is rest(?type_list)
      and pred_list is rest(?pred_list)
      and lag_list is rest(?lag_list).

   end. (* cpm_calc *)

  end. (* total_list *)

 end. (* project_const *)
```

TEXT FILE FOR THE COMPREHENSIVE CODE

```
//description
          *                              *
          * Construction Duration Estimating System *
          *                              *
```

US ARMY CORPS OF ENGINEERS
CONSTRUCTION ENGINEERING RESEARCH LABORATORY

This system is focused on the construction duration estimation of mid-rise buildings of residential/commercial nature. It is limited to buildings with steel, cast in place concrete or masonry structural frame type and with a maximum of two floors below ground. Minimum site work and very simple excavation are assumed. The estimation the system performs is valid for buildings with a typical floor size of up to 25000 square feet per typical floor.

This is a prototype of the system, if you have any questions or comments, please contact Dr. Diego Echeverry at DEPARTMENT OF THE ARMY, CONSTRUCTION ENGINEERING RESEARCH LABORATORY, Construction Management Team, Champaign, Illinois 61824-4005

//

toxic dump site

For toxic dump site, substantial delays should be expected for site cleaning.

//

mobilization

Mobilization is the first activity of the construction.

//

site and foundation

The duration for site preparation and foundation is based on the number of floors below ground. The default values are:

No basement ----- 4 weeks
1 floor of basement ----- 6 weeks
#fyellow <Page Down for more message> #d
2 floors of basement ----- 10 weeks

Site preparation and foundation should start not earlier than March 15 and end not later than December 1. If it happens in this period, a longer duration should be expected.

//

frame erection

The default value of pace of frame erection is 1 week/floor. Duration = number of floors * pace of frame erection.

//

install concrete deck

Install concrete deck is an activity sensitive to weather. If it is performed during hard-freeze prone periods (December through mid March in the Midwest) and temporary protection and heating are not used, substantial delays should be expected.

//

fire proofing

Fire proofing is an activity sensitive to weather.

If it is performed during hard-freeze prone periods (December through mid March in the Midwest) and temporary protection and heating are not used, substantial delays should be expected.
//
Roofing
Roofing is a weather sensitive activity. Normally it requires good weather for its installation (no precipitation, warm temperatures). If it is performed during cold or precipitation intensive periods, substantial delays should be expected.
//
rough in
The activities involved here are plumbing, electrical and HVAC risers and mains.

Duration of rough in = number of floors * pace of frame erection.
//
enclosure installation
Three kinds of enclosure alternatives are considered in the system. Here is a list with the default progression paces:

precast panel/windows --- 2 weeks/floor
glass wall --- 3 weeks/floor
#fyellow <Page Down for more message> #d
masonry/windows --- 2 weeks/floor

Ideally a contractor wants to have the building enclosed prior to the arrival of cold weather. If this is not possible, delays should be expected.
//
elevator installation
Duration of elevator installation may be longer than 12 weeks (default value) to have the same finish time as interior finishing.
//
Interior finishing
The duration of interior finishing is correlated to the amount of interior partition (or walls) to be installed.

finishing of the first floor -- eeks/floor
residential building -- 8 weeks/floor
#fyellow <Page Down for more message> #d
office building:
highly partitioned -- 8 weeks/floor
moderately partitioned -- 5 weeks/floor.

//
clean up
Clean up includes activities like punch-list, final
cleaning and final tests.
//
procurement
Timely, procurement of activity resources with long
lead deliveries or which are scarce in a particular
environment is essential to avoid delays.
//
Weather
Normally it requires good weather condition, warm and
less precipitation, for weather sensitive activities
such as site preparation, foundation, concrete deck
installation, fire proofing, roofing, enclosure, etc.
Otherwise, substantial delays could be expected.
//
Weather-duration
It is a weather sensitive activity. Normally it requires
good weather for its installation (no precipitation,
warm temperatures). If it is going to be performed
during cold or precipitation intensive periods,
substantial delays are expected.
//
type of structure
Two types of structures, steel frame and cast in place
concrete are currently supported by this system. Other
types of structures will be considered in the future.
//
floor area case 1
The system might over estimate for this size of
building footprint. Process will continue.
//
floor area case 3
This range is at the upper limit of the range for which
a floor is not subdivided into work areas. Process will
continue, assuming that 1 floor = 1 work area.
//
floor area case 4
For this range it is very likely that a floor will be
subdivided into two or more work areas. The system does
not handle this case at present.
//

TEXT FILE OF PROCUREMENT MESSAGES

//
frame erection
Structural steel takes more than 12 to 15 weeks to be
delivered after it is ordered.
//

elevator installation
Order elevator one year earlier of installation.
//
enclosure installation
Order windows with necessary anticipation. This may vary between a few weeks to several months.
//
Interior finishing
Order mechanical and electrical equipments with necessary anticipation.
//
procurement
Timely, procurement of activity resources with long lead deliveries or which are scarce in a particular environment is essential to avoid delays.
//

USACERL DISTRIBUTION

Chief of Engineers
ATTN: CEHEC-IM-LH (2)
ATTN: CEHEC-IM-SL (2)
ATTN: CERD-L
ATTN: CEMP-CE
ATTN: CEMP-CP

US Army Engr Districts
ATTN: C/Const Div (41)

US Army Engr Divisions
ATTN: C/Const Div (14)

Ft. Belvoir 22060
ATTN: CECC-R

Defense Technical Info. Center 22304
ATTN: DTIC-FAB (2)

65
7/91

DEPARTMENT OF THE ARMY
CONSTRUCTION ENGINEERING RESEARCH LABORATORY
CORPS OF ENGINEERS
PO BOX 9005
CHAMPAIGN, ILLINOIS 61826-9005

OFFICIAL BUSINESS